Modelling and Dynamic Simulation of a CTMP Plant

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We accept this thesis as conforming
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Abstract

In this thesis, mathematical models for the process units of a chemi-thermomechanical pulping (CTMP) plant have been developed. The models were developed based on first principles and empirical modelling approaches. The models have been used to simulate the dynamic behavior of a CTMP plant. A CTMP plant is composed of four major processes: the chip pretreatment process, the refining process, the pulp processing process, and finally the bleaching process. A mill audit was performed to study the chip quality variations along the chip pretreatment process and typical variations were used for the simulation of a CTMP plant. The refining process was modelled based on the concept of specific energy and refining intensity. The model was used to predict pulp properties and handsheet properties from the refiner operating conditions. Data from mill trials and literature were compared with the prediction and there was good agreement between predicted and measured values. The effects of reject rate on fibre fractionation, freeness, and consistency through the screens were investigated and models were developed. In modelling the bleaching process, a kinetic model was used to relate the final pulp brightness to the hydrogen peroxide charge, temperature, and retention time. The flow pattern of the pulp stock in the bleaching tower was studied and modelled as a combination of continuous stirred tank reactors and a plug flow reactor. The dynamic simulations revealed the impact of the major disturbances and operating conditions on the performance of the whole pulping process. Control strategies have been proposed and tested for the bleaching plant. This work has systematically studied the dynamics of a CTMP plant and brought a thorough understanding of the dynamic behavior of the plant. The models developed in this work can be used as a tool for process modification, process operation, and process control.
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Chapter 1

Introduction

1.1 Background

There are two types of pulping processes, chemical and mechanical pulping. In chemical pulping, the lignin which binds the individual cellulose fibres together is dissolved producing pulps with long, flexible fibres. Chemical pulps produce a strong, compact paper sheet with excellent brightness stability. The main disadvantage of the chemical pulping process is its lower yield (45–50%). Thus, the process is not very resource conserving.

In mechanical pulping, individual fibres are separated using mechanical force resulting in pulps with short, stiff fibres but with high surface area. Since most wood constituents are retained, the pulp yield is higher (90–98%). Mechanical pulps have a lower strength and brightness, a better opacity and printability, and a lower production cost than chemical pulps.

The desire to decrease the use of expensive chemical pulps in the paper machine as well as improving printability in the pressroom has led the way towards higher quality requirements and tighter quality variation on mechanical pulp mills.

1.2 Objectives

There has been a very rapid and substantial increase in the use of computer simulation in the pulp and paper industry in recent years [1–3]. The most common applications have been in the area of process design using general purpose flowsheet simulators, and in the development of control systems for certain areas of the mills. In the 1980’s, there was a general acceptance of simulation as a tool for improving decision making in process design and process operation. Although most of these successful developments have been based on steady-state or quasi-steady-state simulation, the need for dynamic simulation is recognized as a requirement for process optimization and process control.
Steady-state simulators such as GEMS, MASSBAL, GEMCS, MAPPS, PAPMOD, etc. are all based on steady-state mass and energy balances and are used for process design and analysis. Dynamic simulators are necessary for the analysis of process dynamics. They are also necessary for the analysis of the behavior of processes under conditions of start-up, grade changes, and shut downs. Dynamic models can also be employed for the design and testing of control strategies. Together with a distributed control system (DCS) and the necessary software and hardware interfaces, they can be used for testing and final check out of the DCS. Interest in dynamic simulation is growing within the industry. There are many commercial dynamic simulators available now. In most of these packages, the simple, general operating units have been represented by dynamic models. However, many typical, more complex operating units need to be modelled to simulate the dynamics of a pulp and paper mill.

It is the objective of this work to develop a dynamic simulator for a CTMP process, to study the effects of the process variables and disturbances on the pulp quality, and to show the benefits of dynamic simulations. Dynamic simulation can be used to identify the relative importance of the key variables which affect the product quality at different stages of the process, reveal the dynamics of the key operation units and the process as a whole, and design control systems. The simulator can be interfaced with a DCS system to check out new control strategies for CTMP processes before plant commissioning. It can also be used for optimization of the process operation and for operator training.

1.3 Contributions

It is important to note that there have been a few attempts to develop generalized dynamic simulators for the pulp and paper industry; however, high fidelity, mechanistic models for typical operation units are needed to simulate pulping processes such as a chemi-thermomechanical pulping process. This thesis presents the mathematical models for the typical operation units in a CTMP process. In particular, models for chip refiners in a refining process; models for the latency chest, pulp screen and screen network in a pulp processing process; and models for the blend chest, mixer and bleaching tower in a hydrogen peroxide bleaching process have been developed. The models
have been combined to simulate the dynamic behaviour of a CTMP plant and to study the effect of disturbances and operating conditions. The effects of operating variables on the pulp properties were studied. The models of the bleach plant were used to compare different control strategies.

In addition, an audit of the chip pretreatment process was performed to study the chip quality variability along the process. Mill trials of the impacts of motor load and dilution water on the refiner operation were performed. Mill data were obtained from a screen room to tune the model parameters of a screen process. Normal operating data from a hydrogen peroxide bleach process were collected and compared to the model predictions to validate the models.

The major conclusion of this research is to have a dynamic simulation tool for a CTMP plant. One of the applications of the models developed in this thesis were the optimization of the refiner processes and the pulp processing processes. With the models for the entire CTMP plant, the high level hierarchical control a CTMP plant can be tried on the simulator.

1.4 Outline of the Thesis

The thesis is organized as follows:

In chapter 2, a brief introduction is given of a chemi-thermomechanical pulping (CTMP) process.

Chapter 3 presents the results of the chip quality variability study from the mill audit.

Chapter 4 discusses the mechanistic model of the refiners and the predictions of the pulp properties from the operating conditions of the refining system.

In chapter 5, mathematical models for screens and reject refiners are developed and dynamic simulations of the process are performed.

In chapter 6, dynamic simulations of the hydrogen peroxide bleaching process are carried out and control strategies are proposed for the process.

Chapter 7 combines the models for the entire pulping plant and simulates the dynamic behaviours of the overall plant.

Finally, chapter 8 gives a summary of this work and the recommendations for future work.
Chapter 2

Overview of the Mechanical Pulping Process

This chapter first reviews the mechanical pulping process. A typical CTMP process flowsheet and a brief introduction to the CTMP process follow. At the end, we introduce the case study CTMP plant and the simulation package being used.

2.1 The Mechanical Pulping Processes

Mechanical pulps are produced in two different processes - grinding and refining. Substantial information is available [4, 5] describing the sequence of operations involved in producing refiner mechanical pulps. Generally, the refining mechanical pulping process takes place in four steps; (1) chip pretreatment, (2) chip refining, (3) pulp processing and (4) pulp brightening. During the last two decades, the number of refiner mechanical pulping processes has increased dramatically. Today, there exists an entire spectrum of hybrid processes using chemical and mechanical treatments. The most widely used processes are:

RMP : Refiner Mechanical Pulp – atmospheric refining with no pretreatment.

TMP : Thermomechanical Pulping – chips are steamed and refined at an elevated temperature, normally followed by second-stage pressurized or atmospheric refining.

CMP : Chemimechanical Pulping – chips are pretreated with a chemical at an elevated temperature prior to atmospheric refining to produce a pulp yield over 80%.

CTMP : Chemithermomechanical Pulping – chemicals are added to the chips either prior to or during the presteaming of the chips with first-stage refining at an elevated temperature of over 100°C and followed by subsequent atmospheric pressure refining or pressurized refining.
2.2 The CTMP Process

The CTMP process has evolved as a modification of a TMP process, increasing the range of products. It utilizes modest chemical impregnation during the steaming stage, which serves to improve the bonding properties of the pulp and lower the debris content at the expense of a slightly lower scattering coefficient. In conjunction with the peroxide bleaching process, the CTMP process produces high-brightness pulps at reasonable cost.

A schematic for a bleached CTMP plant is shown in Figure 2.1. The plant can be considered as consisting of four major parts: chip pretreatment, two-stage refining, screening and reject refining and pulp brightening.

The unit operations in chip pretreatment consist of: screening to remove over and/or undersize chips; washing to remove contaminants (dirt, sand, grit, knots, etc.); and presteaming to soften the lignin and to drive off entrapped air. Then, the wood chips are impregnated with chemicals, most often sodium sulfite, to improve pulp brightness and strength, and to reduce energy requirements in the refining stages.

The heart of a CTMP system is the disc refiner. In a refiner, there are two or three discs with at least one disc rotating. The equipment available today can be divided into three main categories, based on the disc configuration. The first category is the double-revolving disc refiner which has two counter-rotating discs mounted on cantilevered shafts, each driven by a separate motor. The counter-rotating discs operate at high differential speeds—normally 2400 rpm or 3000 rpm depending on the frequency of the power supply. The material to be refined is fed through the spokes of one of the rotating discs. Both shafts are equipped with thrust bearings and loading is accomplished hydraulically. The second category consists of single-rotating disc refiners, which are available with either cantilevered or through shafts. In both cases, only one disc is rotating at 1800 rpm with 60 Hz power supply, or 1500 rpm with 50 Hz power supply. Feeding the refiner is accomplished through the unrestricted opening of the stationary disc. The third type of refiner is the twin disc refiner which combines two single-rotating disc refiners into one unit. It utilizes both sides of the rotating disc.
instead of just one side. Each side of the rotating disc faces a stationary plate. One stator plate is
normally hydraulically adjusted and loaded against the rotating assembly. The material is fed to the
refiner through the stationary discs.

In a refiner, the chips move through the refining zone between the plates. They are progressively
broken down into small particles, and finally into individual fibres. Water is supplied to the eye of
the refiner to control the refining consistency. In a CTMP plant, refining is usually carried out in
two stages. First-stage refining of chips usually occurs under pressurized conditions. Second-stage
refining usually takes place at atmospheric conditions although high pressure can also be used.

Following chip refining is a process comprising a series of unit operations aimed at enhancing and
controlling pulp quality. These are: latency removal to straighten fibres; screening to remove debris
and shives; cleaning to remove contaminants; and reject refining to reduce debris while making the
long fibres more flexible. Depending on the end use of the pulp, some plants use a bleaching process,
whereas some do not. Hydrogen peroxide bleaching is a common process used for brightening
mechanical pulps. In a hydrogen peroxide bleaching process, the major operating units include a
blend tank to mix different pulp streams together, a press to increase the stock consistency, a mixer
to mix the pulp stock with the bleaching agent, and a retention tower to facilitate the bleaching
reactions.
Figure 2.1: A schematic of a CTMP plant showing the four major processes.
2.3 The Case Study CTMP Plant and the Simulation Package Used

A 325 metric tons per day production line in a CTMP plant located in British Columbia was used as the case study of this work. The plant uses typical thermal and chemical chip treatment processes, a two-stage refining process, screening and reject refining and a hydrogen peroxide brightening plant. We have developed mathematical models from the chip refiner to the bleached storage chest.

To perform the dynamic simulation of the CTMP plant, we used a general purpose dynamic simulator, SIMNON as a platform. SIMNON was developed for simulating dynamic systems whose behaviour is represented by non-linear ordinary differential or difference equations. Subsystems can be connected together to simulate a larger system. This modular feature provides considerable flexibility for constructing plant models, where modules can be easily modified and rearranged for different flowsheets. External modules written in FORTRAN or C can be compiled into the SIMNON to enhance the capability in handling special computational needs. One shortcoming of this simulation package is its lack of user friendly interface. At the time this work was started, there was very little choice. We chose SIMNON as a framework for our simulation studies, but the mathematical models developed for the CTMP process can be easily transferred to other dynamic simulators which have been widely used lately such as SIMULINK, GEMS, IDEAS, ROSE, or PAPDYN.
Chapter 3

Chip Pretreatment Process and Variability Study

Chemi-thermomechanical pulp is made by refining wood chips which are chemically and thermally pretreated. The properties of these pulps are modified by oxidation using sodium sulfite at an elevated temperature. By these means, the wood structure is opened up, the initially hydrophobic lignin becomes more hydrophilic and, after mechanical treatment, the individual fibres become more flexible than RMP fibres. This contributes to improved sheet consolidation and bonding properties, but at the expense of reduced opacity due to a reduction in the light-scattering coefficient. In this chapter, a brief description of a chip pretreatment process is first provided, then some of the results of our mill audit of the chip quality variations are presented. Lastly, there will be discussions on how the chip qualities affect the pulp qualities and how the typical variations of chip quality can be used as a starting point to simulate a CTMP process.

3.1 The Chip Pretreatment Process

Figure 3.1 shows the chip pretreatment process in the CTMP plant under consideration. The mixture of Balsam and Hemlock chips stored in the silos are first conveyed to an active hot water chip washer to remove knots, rocks and metal, to loosen sand that adhere to the chips, and to a lesser degree, to add moisture to the chips, and to defrost the chips during the winter. The washed chips are then pumped to one or two drainers, where the water is drained and sand and fines are further removed. The chips from the drainers are dropped into the presteaming bin where they are heated with low pressure steam. The purpose of presteaming is to elevate the temperature of the chips and to drive off the entrained air that is detrimental to the chemical impregnation process and the heat recovery system. Next, a screw feeder conveys the chips to a press impregnator. The chips are compressed in the press impregnator. The compressed chips are then released at the end of the press impregnator into the discharge chamber where chemicals impregnate the chips. In this particular
process, sodium sulfite ($Na_2SO_3$) and/or sodium bisulfite ($NaHSO_3$) is used. The impregnated chips are sent to a rotary valve by screw conveyors. The rotary valve continuously transfers the chips from the low pressure screw conveyor to a steaming vessel where the chips are heated under pressure. A temperature of about 130°C and retention time of about ten minutes are maintained to facilitate the sulfonation reaction.

Figure 3.1: Flowsheet of the chip pretreatment process in a CTMP plant.

3.2 Chip Quality Variability

Variations in chip quality are bound to happen in this industry and can cause significant variations in pulp quality because of changes in chip size, shape, density, species, moisture content, bark content, contaminants, rot, etc [5]. A great deal of research has been done to investigate the impact of chip quality on pulp quality [6, 7, 8, 9]. It was shown that raw material consisting of chips homogeneous in size gives the best results for pulp properties. Chip size distribution control can be used to optimize the relationship between applied energy and pulp quality. To maximize pulp quality, a moisture
content corresponding to the fibre saturation point (about 30%) [10, 11] should be reached prior to softening in the steaming vessel, and a moisture content corresponding to fully water saturated wood (about 60%) should be reached before entering the refiner. High temperature and prolonged steaming time will cause brightness deterioration of the pulp. The non-uniformity of the chemical impregnation will also adversely affect pulp properties. Kurra et al. reported that if untreated areas are present, the shive content increases rapidly, and the quality of the pulp is lowered [12].

In order to quantify the variability in chip quality and its effects on pulp properties, an audit was performed at our case study mill. Chip samples were collected at different locations along the chip pretreatment process and pulp samples were taken from the secondary refiner. Chip moisture content, chip density and chip thickness fractions were tested. The pulp samples were evaluated for freeness and fibre fractions.

3.2.1 Experimental

To study the process variability, data from critical locations were obtained. Four sampling locations were chosen:

(1) Chip conveyor from the silo to the washer
(2) Bottom of the presteaming bin
(3) Press impregnator discharge
(4) Secondary refiner discharge

Chips and pulp samples were collected during a five hour period, with a sampling interval of 10 minutes, 5 minutes and 2.5 minutes, the latter being the fastest rate physically possible. The samples were taken at all the sampling locations simultaneously.

The chip samples were tested for the following parameters:

(1) Chip moisture content
(2) Chip wet bulk density and dry bulk density
(3) Chip thickness fractions (<2mm, 2-4mm, 4-6mm, 6-8mm, >8mm)
3.2.2 Results and discussions

The time series plots of the chip quality parameters are shown in Appendix C and our findings are summarized below.

3.2.2.1 Chip silos

Wood chips, either purchased or produced in the wood room are stored in the chip silos. Several silos are usually used for chip storage in each production line. From the analysis of the process, it was found that a large periodic variation was caused by switching between two chip silos at this particular mill. The chip size fractions, wet and dry bulk density and moisture content may change significantly as shown in Table 3.1. Table 3.2 shows the chip quality variations after the chip silos during our sampling period.

<table>
<thead>
<tr>
<th>Table 3.1 Chip quality variations in the chip silos.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Wet Bulk Density (kg/m$^3$)</td>
</tr>
<tr>
<td>Dry Bulk Density (kg/m$^3$)</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
</tr>
<tr>
<td>&gt; 8 mm Chip Fraction</td>
</tr>
<tr>
<td>6-8 mm Chip Fraction</td>
</tr>
<tr>
<td>4-6 mm Chip Fraction</td>
</tr>
<tr>
<td>2-4 mm Chip Fraction</td>
</tr>
<tr>
<td>&lt; 2 mm Chip Fraction</td>
</tr>
</tbody>
</table>
Table 3.2 Chip quality variations after the chip silos.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>$\sigma$</th>
<th>$\frac{\sigma}{\text{mean}} \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Bulk Density (kg/m$^3$)</td>
<td>253.1</td>
<td>13.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Dry Bulk Density (kg/m$^3$)</td>
<td>124.2</td>
<td>6.9</td>
<td>5.6</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>51.0</td>
<td>2.1</td>
<td>4.1</td>
</tr>
<tr>
<td>&gt; 8 mm Chip Fraction</td>
<td>0.13</td>
<td>0.046</td>
<td>35.4</td>
</tr>
<tr>
<td>6-8 mm Chip Fraction</td>
<td>0.23</td>
<td>0.047</td>
<td>20.4</td>
</tr>
<tr>
<td>4-6 mm Chip Fraction</td>
<td>0.36</td>
<td>0.024</td>
<td>6.7</td>
</tr>
<tr>
<td>2-4 mm Chip Fraction</td>
<td>0.25</td>
<td>0.062</td>
<td>24.8</td>
</tr>
<tr>
<td>&lt; 2 mm Chip Fraction</td>
<td>0.03</td>
<td>0.012</td>
<td>40.0</td>
</tr>
</tbody>
</table>

3.2.2.2 Presteaming bin

A chip presteaming bin is used to drive off the entrapped air in the void between chips and within the chip structure; it also acts as a preliminary heating stage. The chips are dropped from the chip drainer into the presteaming bin where low pressure steam is introduced from the bottom of the bin. As the steam drives off the air entrapped within the chip and condenses on the chips, the chip moisture content also increases. The chip qualities and their variations are shown in Table 3.3.

The average wet bulk density increases from 253.1 to 324.1 kg/m$^3$ as the chips go through the presteaming bin. This may be due to two occurrences: (1) the removal of thicker and oversize materials in the chip washer and removal of fine chips in the drainer, leading to better packing; and (2) additional moisture being added in the porous interstices of the chips by water and steam diffusion in the presteaming bin. The standard error in chip wet bulk density dropped from 5.1% to 3.8% from silos to presteaming bin. This implies that the chip washer and presteaming bin attenuates the wet bulk variations.
Table 3.3 Chip quality variations in the chip presteaming bin.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>$\sigma$</th>
<th>$\frac{\sigma}{\text{mean}} \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Bulk Density (kg/m$^3$)</td>
<td>324.1</td>
<td>12.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Dry Bulk Density (kg/m$^3$)</td>
<td>124.8</td>
<td>4.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>61.5</td>
<td>1.4</td>
<td>2.3</td>
</tr>
<tr>
<td>&gt; 8 mm Chip Fraction</td>
<td>0.10</td>
<td>0.022</td>
<td>22</td>
</tr>
<tr>
<td>6-8 mm Chip Fraction</td>
<td>0.18</td>
<td>0.026</td>
<td>14.4</td>
</tr>
<tr>
<td>4-6 mm Chip Fraction</td>
<td>0.37</td>
<td>0.023</td>
<td>6.2</td>
</tr>
<tr>
<td>2-4 mm Chip Fraction</td>
<td>0.30</td>
<td>0.033</td>
<td>11.0</td>
</tr>
<tr>
<td>&lt; 2 mm Chip Fraction</td>
<td>0.05</td>
<td>0.009</td>
<td>18.0</td>
</tr>
</tbody>
</table>

The average chip moisture content from the presteaming bin (61.5%) is higher than that from the chip silos (51.0%) due to water diffusion in the chip washer and steam diffusion in the presteaming bin. The standard error of the moisture content from the presteaming bin is lower than that from the chip silos (2.3% versus 4.1%). From chip silo to chip presteaming bin, the chip size distribution is shifted to the thinner side. The average chip thickness shifts from 5.36 millimeters to 4.96 millimeters.

3.2.2.3 Press impregnator

Chip quality variations after the press impregnator are shown in Table 3.4.

A press impregnator is actually a plug screw feeder with a compression ratio, typically between 2:1 and 5:1. Heitner et al.[13] have shown that a significant difference exists between pulps produced at a compression ratio of 2:1 or less, and those produced at a 4:1 ratio or higher. The high compression ratio is beneficial to the final pulp, improving tear and tensile strengths [13]. Recent investigation by Parkinson et al.[14] found that at a compression ratio of 5:1, the fibres become damaged and hence the fibre length decreases. However, an industrial press impregnator for a specific process usually has a fixed compression ratio. The one used at this mill has a compression ratio of 3:1.
Table 3.4 Chip quality variations in press impregnator.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>σ</th>
<th>$\frac{\sigma}{\text{mean}} \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Bulk Density (kg/m³)</td>
<td>186.4</td>
<td>13.2</td>
<td>7.1</td>
</tr>
<tr>
<td>Dry Bulk Density (kg/m³)</td>
<td>97.7</td>
<td>4.3</td>
<td>4.4</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>47.5</td>
<td>2.4</td>
<td>5.1</td>
</tr>
<tr>
<td>&gt; 8 mm Chip Fraction</td>
<td>0.08</td>
<td>0.019</td>
<td>23.8</td>
</tr>
<tr>
<td>6-8 mm Chip Fraction</td>
<td>0.17</td>
<td>0.024</td>
<td>14.1</td>
</tr>
<tr>
<td>4-6 mm Chip Fraction</td>
<td>0.32</td>
<td>0.014</td>
<td>4.4</td>
</tr>
<tr>
<td>2-4 mm Chip Fraction</td>
<td>0.31</td>
<td>0.028</td>
<td>9.0</td>
</tr>
<tr>
<td>&lt; 2 mm Chip Fraction</td>
<td>0.12</td>
<td>0.009</td>
<td>7.5</td>
</tr>
</tbody>
</table>

While impregnation is the main objective of the press impregnator, extensive chip breakage takes place in the press impregnator. This induces a change in the chip size distribution which will affect chemical uptake during impregnation and energy consumption during refining. It has been shown that considerable energy can be saved by minimizing the proportion of oversized chips while smaller chips may produce pulp with less strength [15].

From the experiments, we have learned that the chip breakage inside a press impregnator is not simply one chip breaking into two or more pieces of smaller size. After a close examination of the chip sample before and after the press impregnator, we found that the mechanical treatment of chips is quite severe and is more complicated than a simple breakage. At least four types of treatments could be identified from the audit performed at the mill.

Type 1: A chip can be broken into two or more pieces. This results in a decrease in the large fractions and an increase in the small fractions.

Type 2: A chip can be delaminated. Gaps are created within the chip along the annual rings forming different layers that are still linked together. The chip remains a single entity but new
surfaces are created. As a result of the delamination, one dimension of the chip actually increases and results in a lower bulk density. When the different layers are separated the chips belong to type 1.

Type 3: A chip can be squeezed at one end and left basically untouched at the other end. The chip looks like a broom.

Type 4: A chip can be squeezed and released somewhat like a sponge. The apparent volume of the chip remains basically unchanged but fissures and cracks have been created.

We also observed a decrease in the chip dry bulk density from the mill audit. We found a chip dry bulk density of 124.8 kg/m$^3$ before the press impregnator while it dropped to 97.7 kg/m$^3$ after the press impregnator, which can be explained by the delamination and brooming effect we just described.

The average chip wet bulk density decreases from 324.1 kg/m$^3$ to 186.4 kg/m$^3$ as the chips move from the presteaming bin to the press impregnator. This is mainly due to the reduction in moisture content after the press impregnator as well as the reduction in dry bulk density. The standard error in the wet bulk density of the chips from the press impregnator is much higher than that from the presteaming bin (7.1% versus 3.8%). This may be due to the non-uniform application of sodium sulfate solution at the end of press impregnation. The variation could possibly be reduced if chemical soaking was used instead of chemical spraying in the press impregnator.

The chip moisture content from the press impregnator (47.5%) is lower than that from the presteaming bin (61.5%) due to the squeezing action applied in the press impregnator. The chemical spray results in low liquor uptake because it does not sufficiently replace the moisture lost during pressing. The standard error in the moisture content from the press impregnator is significantly higher than that of the presteaming bin (5.0% versus 2.3%). This again may be attributed to the spraying of the chemical solution which resulted in non-uniform liquor uptake. Based on these results, it appears that the impregnation method used in this process does not attenuate the density and moisture content variations but rather contributes to them.

The design and operation of a press impregnator have a very important effect on chemical impregnation. In a press impregnator, chips are compressed, and air and water are squeezed out. Once
released, chips expand, soaking in the liquor somewhat like a sponge. The compression ratio of the press impregnator plays an important role in determining the extent of chemical impregnation. Apart from the compression ratio, other parameters such as wood density, porosity, pore size distribution, initial chip moisture content, chip size distribution and chemical flow rate and concentration will affect the chemical impregnation of the chips. Besides the suction force caused by chip expansion, the difference in temperature between the liquor and the chips will also influence the impregnation. Because of the lower temperature of the chemical solution, the gas volume inside the chips decreases. This phenomenon creates a partial vacuum that draws the liquor into the lumens [16]. Understanding of the chemical uptake process is still limited, and it is difficult at this stage to derive a mechanistic model that would include all these effects.

3.2.2.4 Steaming vessel

After impregnation, the chip temperature must be increased so the sulfonation reaction can take place. Chip temperature is increased by placing chips in a steaming vessel under pressurized conditions. Ferritsius and Moldenius [17] reported that when the sulfite was added before the steaming vessel, approximately 80% of the sulfonation occurred during the preheating of chips in the steaming vessel, 15% during refining and 5% after the refining. When the sulfite was added directly to the refiner, or if the steaming vessel was not facilitating the sulfonation well, the pulp had a higher shive content, the tensile index at a given freeness was somewhat lower and the surface roughness was appreciatively higher. A steaming vessel should provide enough residence time for chip sulfonation. On the other hand, too high a temperature can cause brightness deterioration. In our mill audit, due to physical restrictions, we could not take samples from the steaming vessel.

3.3 Summary

The chip pretreatment process is a very complex process. Due to the discrete nature of chip flow and lack of sensors for the measurements of the chip qualities, it is very difficult to model the process. In this work, we performed a mill audit on the chip quality variations and used these variations as the starting point for the dynamic simulation of a CTMP process.
The mill study showed that large variations in chip quality existed. It was found that the chip presteaming bin attenuated the variations in chip density and chip moisture content. Large variations were introduced in chip density and moisture content in the press impregnator because of the chemical spray used at the end of the press impregnator. Complicated type of chip deformation was observed in the press impregnator.
Chapter 4

Chip Refining Process

4.1 Literature Review

The chip refiner is the heart of a CTMP process. The wood chips to be refined are introduced via a screwfeeder into the eye of the refiner. As the material moves through the refining zone between the revolving plates, it is progressively broken down into smaller particles and finally into fibres and fibre pieces. Water is supplied to the eye of the refiner to adjust the refining consistency.

Chip refining is usually carried out in two stages. A schematic of the refining process is shown in Figure 4.1. The primary refiner is usually operated under pressure. The refined material is blown out into a cyclone, where fibres and steam are separated. The secondary refiner further refines the fibres and usually operates at a lower pressure than that of the primary refiner. Once again, fibres and steam are separated in a cyclone after the secondary refiner. The pulp is sent to the latency chest where it is mixed with hot water for latency removal and dilution. The steam from the cyclones is fed to the heat recovery system and part of it is used in the chip pretreatment process.

The refining process is known as a very complex system because of the complexity of the interactions and relationships between the variations of raw material, operating conditions and the resulting pulp properties.

Considerable research has been carried out on the theoretical study of chip refining, and significant progress has been made towards a better understanding of the mechanisms involved. Attack and May [18] suggested that the breakdown of chips in a chip refiner may result from the compression and rolling of chip fragments in the refining zone, and that there are distinct phases in the reduction of chips. In the breaker bar section of the refiner plates, chips are reduced into matchstick fragments. Further breakdown of these fragments occurs by a process in which many of them are in contact
with the surface of both refiner plates. Lastly, small fragments, finer than the spacing between the plates, are refined into pulp.

Aarni and Virkkunen [19] developed a mathematical model which was used to calculate the pressure and velocity profile of steam and water and wood flow inside a refiner. They also studied the effect of the shape and length of the refining zone on steam flow and energy consumption. Strand [20] applied the comminution theory to describe the fibre size reduction inside a refiner. Ruscio and Balchen [21] developed a mathematical model to describe the particle size reduction inside a refiner. The model relates the feed fibre size distribution to outlet fibre size distribution by breakage rates which are estimated from the experimental data.

Miles and May [22, 23] showed that the flow of pulp and residence time in the refiner are of critical importance in refining. The residence time of the pulp in the refining zone of a chip refiner determines the average number of bar impacts per fibre. For a given specific energy, the residence time controls the refining intensity. Refining intensity is defined as the average amount of specific
energy transferred at each impact. The concept of refining intensity implies that the quality of the pulp will depend not only on the specific energy applied, but also on the intensity of its application. The residence time and the refining intensity can be calculated from the equations derived by Miles and May [22] for the flow of pulp in a chip refiner under a variety of operating conditions. The refining intensity is affected by the specific energy, inlet consistency, rotational speed of the discs and the plate pattern. A pilot plant study was carried out by Cort et al [24] to determine the effect of high speed refining on energy consumption and pulp quality, and the conclusion was that high speed refining offers a significant advantage in day to day operating expenses while still enhancing the pulp quality. Senger et al [25] studied the effect of pulp furnish and refiner speed on residence time in a high consistency refiner and found that lower rotational speeds produced larger residence times. The rotational speed of a refiner plate is one of the most important variables which determine the pulp quality and energy consumption. This is because the rotational speed will affect both the impulse moment of the bars and the residence time of the pulp inside the refiner. Many researchers have contributed to this area of study [26–28].

The study by Hoglund et al.[29] showed how wood characteristics influence pulp properties. They showed that pulp characteristics obtained from different wood species, treated in a similar manner, may differ significantly. A recent study by Stationwala [30] and his colleagues showed that with the same process equipment, different wood species produce different qualities of pulp. A series of studies have been done to quantify the influence of wood characteristics and chip quality on pulp properties [15, 31, 9, 32]. The results indicated the importance of uniformity of chip size and chip density. Fines, knots and bark all have detrimental effects on pulp quality.

In the CTMP process, the effects of preheating, impregnation, chemical addition and refiner housing pressure play important roles in obtaining a target pulp quality [12, 17, 33]. The temperature and pressure in the refining zone have been measured in some cases [34, 35]. It is known that the type of fibre separation during refining is dependent upon temperature. Giertz [36] reported that the lignin softening temperature is 125°C for spruce and is in the range of 110 to 115°C for hardwoods. Koran [37] showed that at temperatures below 120°C, fibre separation takes place in the primary wall
Chapter 4: Chip Refining Process

for black spruce. This provides a cellulose-rich surface, resulting in better bonding between fibres but shorter fibre lengths. Above 150°C, fibre separation occurs predominantly at the interface between the middle lamella and the primary wall in the softened lignin. Some fibres may not be separated. The resulting fibre surfaces are smooth, and the fibres are covered with lignin, which makes them stiff and does not provide very good bonding. However, the separated fibres are longer [38]. The effect of refiner housing pressure and the presteaming time is mainly on the brightness of the pulp. By increasing the pressure, the brightness will decrease. However, this can be compensated for by shortening the preheating time [39].

In summary, much research has been carried out and is ongoing to study the effects of process variables on the pulp properties in the refining process. Research is generally focused on certain specific unit operations and process variables are sometimes isolated for the study. There is however a need for a comprehensive mathematical model to represent the complex interactions and relationships between the operating conditions, the disturbances, and the pulp properties. A systematic analysis of the process is needed to study these interactions and interrelations. In this work, a mathematical model is developed to describe the relationships among the operating variables, the disturbances, and the pulp properties. Simulations are performed to study the effect of manipulated variables and disturbances on the product properties.

4.2 Model Development

Before developing the mathematical model, it is important to select the variables that are used to represent the process. In the following, we list the common variables used to represent the operation of refiners, and the pulp properties.

4.2.1 Process variables

For the modelling of the refining process, we categorize the process variables into five sets: primary variables, secondary variables, disturbances, passive variables and output variables.
Chapter 4: Chip Refining Process

4.2.1.1 Primary variables

The primary variables are those which are manipulated by the operators or by the control systems to control the refining conditions. In the operation of refiners, the primary variables are:

i. electro-mechanical or hydraulic load applied to the refiner plates to adjust the axial thrust;
ii. transfer screw feeder speed which is used to alter the feed rate of wood chips;
iii. dilution water flow rate to adjust the inlet consistency and consequently the refining consistency.

4.2.1.2 Secondary variables

The secondary variables are used to describe the operating conditions of a refining system. The secondary variables are related to and depend upon the primary operating variables:

i. motor load
ii. production rate (throughput)
iii. specific energy
iv. inlet and outlet consistency
v. plate gap
vi. residence time
vii. refining intensity
viii. specific refining power

4.2.1.3 Disturbances

The major disturbances to the operation of a refiner are associated with the wood chips, except for the wearing of the refiner plates and dilution water temperature.

i. wood species
ii. chip size distribution
iii. chip bulk density
iv. chip moisture content
v. chip temperature
vi. sulfonate content
vii. plate wear
viii. dilution water temperature

4.2.1.4 Passive process variables (design specifications)

The passive variables are those variables that depend upon the design of the refiner. They affect the operation of the refining system, but they are fixed for a given refiner. These variables include:
i. plate geometry

ii. bar material

iii. disc rotational speed

It has been shown [26–28, 40] that the rotational speed of a refiner plate is a critical variable in determining pulp quality and energy consumption. This is due to the fact that the rotational speed affects the residence time of the fibres between the plates. However, since fixed speed refiners are widely used in the industry, the rotational speed will not be taken as a manipulated variable in this study.

4.2.1.5 Output variables

The aim of chip refining is to produce pulp of a specific quality. Normally it means that the fibres should be flexible, have good bonding ability, and the fibre length and drainage are suitable for good sheet formation, strength, and runnability. Further improvements in paper quality are dependent upon quality control in the pulping area.

A large number of fibre properties such as fibre length, coarseness, fibrillation, and flexibility are responsible for the final pulp and paper quality (freeness, burst, tear, breaking length, etc). It can be assumed that there are certain basic quality factors of the pulp which have a physical background, are independent of each other, and which have an effect on measurable quality parameters. In the early work of Forgacs [41], the author assumed that the structural composition of stone groundwood pulps could be defined by the distribution by weight of fibre length (L-factor, percent weight of fibre retained on the 48 Mesh screen of the Bauer-McNett classifier) and a particle shape factor (S-factor, specific surface area of the fibres passing the 48 mesh screen but retained on the 100 Mesh screen of the Bauer-McNett classifier) which describe the relative properties of ribbon like and chunky materials. The importance of the specific surface area as a measure of pulp quality has been recognized by several investigators [42–44]. Karnis et al. [45, 46] devised methods for the rapid determination of Forgacs’ L and S-factors.
Several researchers [47, 48] have demonstrated the importance of shives in influencing pulp properties and papermaking potential. Shives is defined as intact fibre bundles and other such fragments present in the pulp. The shive content of pulps is defined as the percentage, based on oven-dry mass, of pulp retained on a standard slotted fractionating plate. It has been commonly measured by the Somerville fractionator. Shive can also be measured by shive count, which is a quantitative measurement of shive concentration based on counting the number of shives present in a pulp sheet or handsheet of know mass. Norberg [49] has shown that it is possible for pulps with identical Bauer-McNett classifications to have different strength and drainage properties due to the presence of shives.

There is a variety of tests in the pulp and paper industry which are used to characterize the papermaking ability of mechanical pulps. However, it has been repeatedly observed that a large portion of the variation in these tests can be attributed to relatively few “common factors” which link together the pulp properties. In a study to identify a minimum number of characterizing parameters to evaluate pulp quality Venkatesh [50] found that freeness, Somerville shive content, and long fibre (+28 Mesh) are the three basic pulp characteristics which adequately describe mechanical pulps. A study by Strand [51] on the relationship between the intrinsic fibre properties (such as fibre size distribution, specific surface area, fibre flexibility) and pulp quality test (such as tensile index, burst index, tear index, light scattering coefficient) using factor analysis indicated that 92% of the variation of the pulp quality properties could be explained by two common factors which are related to fibre length and bonding property. Heikkurinen [52] defined basic fibre properties as those fibre properties that are independent of each other and suggested that fibre size distribution (fibre length, fibre width and cell wall thickness), shape (specific surface, external fibrillation, curl), surface properties (chemical composition, fibril angle), and the structure of the fibre wall (flexibility, swellability, pore volume, etc) are the properties that determine the status of the pulp. Changes in any of these properties affect pulp quality, and in principle, any of them can be varied without affecting the others. Broderick et al [53] investigated the link between the fibre characteristic and handsheet properties of a high-yield pulp. Many physical and chemical characteristics, including specific surface, flexibility, Klason
lignin, and pentosan index were examined. They developed latent vector models that accounted for more than 75% of the variations in handsheet properties.

From a process control point of view, the choice of the parameters to characterize pulp quality is linked to the availability of on-line measurements. Due to the lack of adequate sensors, mechanical pulp is traditionally characterized by freeness or drainage value, expressed in CSF or °SR. Some well known developments in on-line measurement of pulp quality are the PQM 400 and Pulp Expert. The PQM 400 is an automated device for on-line measurement of drainage time, fibre length distributions and optical shive distribution [54]. The Pulp Expert measures consistency, drainage, brightness, dirt content, and fibre length distribution. In our study,

i. Canadian Standard Freeness
ii. long fibre fraction (+28 and 28/48)
iii. shive content

are used to characterize pulp quality. These properties can be measured on-line with a PQM 400 or a Pulp Expert fibre analyzer.

The variables governing a refiner operation are summarized in Figure 4.2:
**Figure 4.2:** Variables of a refiner
4.2.2 Relationships between primary variables, disturbances and secondary variables

The proposed model structure for the refining system is illustrated in Figure 4.3; each equation will be discussed below.

4.2.2.1 Production rate

The production rate is defined as the mass flow rate of oven dry wood into the refiner per unit of time. The wood chips are fed to the refiner by a transfer screw feeder. The flow rate of chips is adjusted by changing the screw feeder speed. The production rate can then be expressed as

\[ F_c = \frac{1}{60} \cdot k_{ts} \cdot \rho_{stv} \cdot TS_{rpm} \]  

where

- \( TS_{rpm} \) is the rotational speed of the transfer screw feeder.
- \( \rho_{stv} \) is the chip bulk density.
- \( k_{ts} \) is a coefficient which can be calibrated from mill data for a given screwfeeder. \( k_{ts} \) for the screwfeeder used in this case study is \( 7.56 \times 10^{-2} \) m\(^3\)/rev

4.2.2.2 Motor load

Studies [20, 22, 55] have shown that the refiner motor load is a very complex variable which depends mainly on the axial thrust applied to the refiner plates, the production rate, and inlet consistency. Wood species or wood density also affects the motor load. However, the effect of wood species was not considered in modelling the motor load.

Extensive research has addressed the relationships between closing pressure, throughput (production rate), inlet consistency and refiner motor load. Refining force equal to total axial thrust on the refining zone is balanced by an equal reaction thrust inside the refining zone. It has been shown [34] that this reaction thrust is the sum of the reaction thrust exerted by the steam pressure on the refining plates and the reaction thrust exerted by the wood material squeezed between the refining plate surfaces. Franzen and Sweitzer [56] observed that in practice the steam thrust also increases in
Chapter 4: Chip Refining Process

Figure 4.3: Model structure of a refining system
proportion to the throughput. This was also predicted by Miles and May’s [23] constitutive model.

Cluett, Guan and Duever [57] have observed that the dynamic relationship between the chip feed transfer screw speed and the motor load is of a first order plus delay characteristic. The average step response exhibited a gain of 70 (kw/% screw speed) and a time constant of 7 seconds for the refiner of their trial.

Based on research results summarized above, we found that for a hydraulic loading system the relationship between closing pressure and production rate and motor load can be described as follows:

\[ ML = ML_0 + k_2 \cdot CP + k_3 \cdot F_c \]  

(4.2)

where

- \( ML \) = motor load (kw)
- \( ML_0 \) = motor load at the normal operating condition (kw)
- \( CP \) = hydraulic closing pressure of a refiner (kPa)
- \( F_c \) = chip flow rate to refiner (kg/s)

However, it should be noted here that the equation above only applies to the normal operating range around the operating point. Dumont [58] reported that there is a maximum motor load corresponding to a plate gap below which the pulp pad between the refiner plates can not sustain the pressure and collapses. This causes the incremental gain between the motor load and the plate gap to change the sign. The refiner must be operated in the region where closing the gap increases the load, or in other word, increasing the closing pressure increases the motor load.

4.2.2.3 Inlet consistency

The inlet consistency is dependent upon the production rate, chip moisture content, dilution water, and seal water flow rate. A mass balance can be written to calculate the inlet consistency

\[ C_i = \frac{F_c}{1 - M \cdot F_c + F_{dw}} \]  

(4.3)
where

\[ F_{dw} = \text{dilution water flow rate (kg/s)} \]
\[ M = \text{chip moisture content (fractional)} \]
\[ F_c = \text{production rate (kg/s)} \]

4.2.2.4 Outlet consistency

The outlet consistency can be calculated based on mass and energy balances. The derivation of the equations is shown in the following.

The input and output variables pertinent to mass and energy balances of a refiner are shown in Figure 4.4.

The chip flow rate is \( F_c \). Water carried by the chip as moisture is \( F_{wi} \), which is given by:

\[ F_{wi} = \frac{M}{1 - M} F_c \]  \((4.4)\)

Dilution water and seal water flow rate are \( F_{dw} \) and \( F_{sw} \) respectively. Assuming the pulp yield is 100% for the mass and energy balance equations, the fibre flow rate out of the refiner is the same as the chip flow rate. Water leaving the refiner with pulp is denoted as \( F_{wo} \) and steam flow rate from the refiner is \( F_s \). Then the water balance becomes:
To write the total energy balance, energy entering and exiting the refiner are listed as follows:

The energy input with the chips is:

\[ F_{wi}C_wT_i + F_cC_cT_i \]  \hspace{1cm} (4.6)

the energy supplied by the motor is:

\[ \eta \times ML \]  \hspace{1cm} (4.7)

where \( \eta \) is the motor efficiency;

the energy in the dilution and seal water is:

\[ F_{dw}C_wT_d \]  \hspace{1cm} (4.8)

the energy in the pulp is:

\[ F_cC_cT_o + F_{wo}C_wT_o \]  \hspace{1cm} (4.9)

the energy in the steam is:

\[ F_sH_s \]  \hspace{1cm} (4.10)

and the energy loss is:

\[ E_l = \epsilon(\eta \times ML) \]  \hspace{1cm} (4.11)

where it is assumed that the heat loss from the refiner is proportional to the motor load by a factor \( \epsilon \).
Assuming there was no back flow steam condensation on the incoming chips, then the overall steady-state energy balance of the refiner is given by:

\[ F_c c_c T_i + F_w c_w T_i + F_d w c_w T_d + (1 - \epsilon) \eta M L = F_c c_c T_o + F_w o c_w T_o + F_s H_s \]  \hspace{1cm} (4.12)

From equation (4.5) and (4.12), \( F_w o \) and \( F_s \) become:

\[ F_w o = F_w i + F_d w - F_s \]  \hspace{1cm} (4.13)

\[ F_s = \frac{(1 - \epsilon) \eta M L - F_w c_w (T_o - T_i) - F_c c_c (T_o - T_i) - F_d w c_w (T_o - T_d)}{H_s - c_w T_o} \]  \hspace{1cm} (4.14)

The outlet consistency can be calculated from the chip flow rate and the water leaving the refiner in the stock as follows:

\[ C_o = \frac{F_c}{F_w o + F_c} \]  \hspace{1cm} (4.15)

### 4.2.2.5 Specific energy

The total power applied to a refiner can be divided into two parts. First, there is a backed off power, which represents the power needed to keep the refiner plate rotating when there are no chips in between the plates. Second, there is a net power, which represents the power to break the chips and refine the fibres. The net power is the difference between the total power and the backed off power. However, in practice, the specific energy is calculated using the total power. Thus the specific energy of a refiner is defined as follows:

\[ SE = \frac{M L}{F_c} \]  \hspace{1cm} (4.16)

### 4.2.2.6 Refining intensity

In practice, the specific energy is generally manipulated to control the pulp freeness; however, this is now recognized to be insufficient. Most people agree that at least two control variables are required to control the pulp properties. The way in which the total energy is applied has a substantial
effect on the pulp quality. How the energy is applied is measured by the refining intensity which was defined by Miles and May [22] as the specific energy per impact. The number of impacts received by the fibres is determined by the rotational speed of the refiner, the number of bars per unit length of arc on the refiner discs, and the residence time of the pulp within the refining zone.

A simplified equation for calculating the residence time in a chip refiner has been developed [59]. The equation was derived based on a force balance inside a refiner with an assumption that of the effect of the steam flow can be neglected. The equation is given below:

\[
T = \frac{Mr}{Ht \cdot u^3 \cdot (L + C_i \cdot r_{l} - r_{t}) + C_i \cdot SE - r_{l}} \cdot n^2 \cdot SE
\]

(4.17)

where

- \( \tau \) is the residence time (s)
- \( C_i \) is inlet consistency (fractional)
- \( \mu_r, \mu_t \) are the radial and tangential friction coefficients between the pulp and the discs
- \( \omega \) is the specified speed of rotation of the refiner (rad/s)
- \( a \) is 4 for a single-disc refiner and 2 for a double-disc refiner
- \( L_s \) is the latent heat of steam at the refining pressure (kJ/kg)
- \( r_1, r_2 \) are the inlet and outlet radii of the refining zone (mm)

Measurement of the residence time is a good method of monitoring the refining conditions inside a refiner. The first attempt was by May et al [60] who developed a technique to measure the residence time in a pilot plant chip refiner. More recently, Ouellet and co-workers [61] developed a system to measure the pulp residence time in a laboratory high-consistency refiner using fibre optic probes positioned around the inner and outer radii of the refiner stator disc.

The total number of impacts \( N \) is proportional to the residence time, and is given by [59]:

\[
N = n \cdot h \cdot \omega \cdot \frac{r_1 + r_2}{2} \tau
\]

(4.18)
where

\( n \) is the number of bars per unit length of arc

\( h \) is 1 for a single disc refiner and 2 for a double disc refiner

The average specific energy per impact is then given by:

\[
\bar{e} = \frac{SE}{N}
\]  
(4.19)

where

\( e \) is the average specific energy per bar impact;

\( N \) is the total number of bar impacts.

Due to the fact that wood is a viscoelastic material, its properties depend not only on the amount of energy absorbed per impact, but also on the rate at which this energy is transferred. To describe this energy transfer rate, Miles [26] introduced the specific refining power defined as:

\[
\dot{e} = \frac{SE}{\tau}
\]  
(4.20)

4.2.3 Relationship between refining conditions and pulp properties

Many properties can be used to describe pulp quality. As previously mentioned, we decided to look at freeness, long fibre content, and shive content since at the present time these properties can be reasonably well measured on-line.

4.2.3.1 Freeness

There is much research on the relationship between pulp freeness and the operating conditions of a refiner. Many empirical equations have been developed, based on specific sets of experimental
data. We did an extensive search of the existing empirical relationships for TMP and CTMP pulp freeness. They are summarized in Table 4.1.

\[
\begin{align*}
\Delta CSF &= -0.50 \cdot \Delta SE - 103.6 \cdot \Delta PR - 0.05 \cdot \Delta PA \quad (4.21) \quad [51] \\
\Delta CSF &= -0.36 \cdot \Delta SE \quad (4.22) \quad [51] \\
\Delta CSF &= -0.40 \cdot \Delta SE \quad (4.23) \quad [33] \\
\Delta CSF &= -0.25 \cdot \Delta SE \quad (4.24) \quad [24] \\
\Delta CSF &= -0.32 \cdot \Delta SE \quad (4.25) \quad [32]
\end{align*}
\]

**Table 4.1** Empirical equations predicting the freeness from specific energy.

In the equations, the Canadian Standard Freeness, CSF is in ml, the specific energy, SE is in kwhr/odmt, production rate, PR is in odmt/hr, the plate age, PA is in hour.

Most of them relate freeness change to specific energy (\(\Delta SE\)). Strand and Mokvist [20] found that production rate (\(\Delta PR\)) and plate age (\(\Delta PA\)) also had some effects on pulp freeness. However, it has been widely accepted that apart from the specific energy, refining intensity is another variable which has major effect on the freeness. Experimental data from Miles [26] showed a good linear relationship between the logarithm of freeness and refining intensity as characterized by specific energy per bar impact. At a constant specific energy, the effect of sulfonate content on freeness depends upon the degree of sulfonation [62]. For a low degree of sulfonation (0—1.8%), freeness increases with sulfonate content, while for a high degree of sulfonation (>1.8%), freeness decreases with the increasing sulfonate content. In a typical CTMP process, the sulfonate content is generally below 0.8%, and freeness will therefore increase with sulfonate content. Based on the results as reported above, we propose the format of equation to describe the combined effect of refining intensity,
specific energy and sulfonation on pulp freeness as follows. The model parameters were estimated using the non-linear least squares method.

\[
CSF = (CSF_0 - k_4 \cdot (SE - SE_0)) \cdot 10^{k_5 (\varepsilon - \varepsilon_0)} + k_6 \cdot C_{SO_3}
\]  

(4.26)

where:

\(CSF_0, SE_0, \) and \(\varepsilon_0\) correspond to a nominal operation point and depend upon the refining process and the raw material characteristics.

\(C_{SO_3}\) is the sulfonate content of wood in per cent of oven dry wood.

\(k_4, k_5, \) and \(k_6\) are parameters. For this particular set of data, the model parameters \(k_4, k_5, \) and \(k_6\) were found to be 0.106, 0.114 and 191 respectively.

![Figure 4.5: Model predicted freeness and experimental data points.](image)
A comparison between the model predictions and experimental data points is shown in Figure 4.5. As shown in the figure, the model predictions are good over a fairly wide range of specific energies and refining intensities.

### 4.2.3.2 Long fibre content

Another very important pulp property is the long fibre content, which is defined as the percent weight of fibres retained on the 48 mesh screen of the Bauer-McNett classifier. A few studies have shown that the reduction of the long fibre content was proportional to the total specific energy [20, 33]. The long fibre content seems to be linearly related to the specific refining power at a constant specific energy, according to results reported by Miles [26]. Ferritsius and Moldenius [63] reported that the long fibre content and the sulfonate content follow a linear relationship when the pulp is refined to a constant freeness level. We therefore propose the format of the equation to relate specific energy, specific refining power, and sulfonate content to the long fibre content as follows.

\[
LF = LF_0 - k_7 \cdot (\dot{e} - \dot{e}_0) - k_8 \cdot (SE - SE_0) + k_9 \cdot C_{so3}
\] (4.27)

where:

- \(LF_0\), \(SE_0\), and \(\dot{e}_0\) are the nominal values of long fibre content, specific energy and specific refining power.
- \(k_7\), \(k_8\), and \(k_9\) are model parameters. Using the least squares method, it was found that \(k_7\), \(k_8\), and \(k_9\) were 2.1, 0.0041 and 9.6 respectively.

Figure 4.6 shows the model predictions are in good agreement with the experimental data.

### 4.2.3.3 Shive content

There is very little information available about the relationships between refiner operating conditions and shive content. The logarithm of the shive content was found to be linearly related to the specific refining power at a constant specific energy [26]. Similarly, at a constant specific
refining power level, the shive content decreases logarithmically with increasing specific energy. In addition, Ferritsius and Moldenius [63] reported that the shive content is an exponential function of the sulfonate content. Based on these reported results, we present the following equation format to predict the shive content from specific energy, specific refining power and sulfonate content:

\[
SC = SC_0 \cdot 10^{-\left[k_{10}(SE-SE_0)+k_{11}(e-e_0)+k_{12}\cdot C_{sec}\right]}
\] (4.28)

where \(SC_0\) is a nominal value of shive content. \(k_{10}, k_{11}\) and \(k_{12}\) are the model parameters. Again the least squares method was used to estimate the model parameters from the data and \(k_{10}, k_{11}\) and \(k_{12}\) were found to be 0.00426, 0.056 and 0.2 respectively.

Figure 4.7 shows the shive contents of the pilot plant refiner and the model prediction. Again, the model prediction and the data are in a good agreement.

The above pulp quality models were developed from many experimental studies, especially from the studies reported by Miles [26], Strand [51], and Ferritsius and Moldenius [63]. All the parameters
5(K

Specific Energy (kJ/kg) Specific Refining Power (MJ/kg/s)

Figure 4.7: Model predicted shive content and experimental data.

in the equations (4.26, 4.27, 4.28) depended upon the type of refiner and need to be calibrated from
the day-to-day operational data or from experimental data.

4.2.4 Relationship between pulp properties and handsheet properties

Many researchers have discussed the characterization of mechanical pulp fibres [41–43, 64–66]. Regression techniques have been used by several researchers to relate pulp handsheet properties to mechanical pulp characteristics under specific conditions and are limited to these conditions [41, 66–68]. Such relationships can be used for mill control, as the pulp quality can be gauged on the basis of a few mill measurements. Venkatesh [50] identified freeness, shive content, and long fibre content (+28) as the three pulp characteristics which could describe mechanical pulps and predict handsheet strength and pulp drainage properties. By using a multiple regression technique on data from the literature, empirical equations to predict the drainage time, burst, tear, breaking length, bulk and wet strength for mechanical pulp handsheets as a function of the freeness, shive content and long fibre content were established [50]. These equations were validated with both literature and mill data. It was reported by Venkatesh that the regression equations from a specific mill gave a
prediction accuracy of about 84%. However, the multiple linear regression techniques are sometimes insufficient to handle the large set of independent variables.

Broderick [69] et al have used partial least squares to model the relationships between some intrinsic fibre properties and handsheet properties. Principal component analysis [70] is also an effective method to determine the most important variables among the independent variables. We used principal component analysis to analyze a set of data from literature [51]. We tried different combinations of original variables, different transformations of the original variables to reduce the total prediction error. It was found that the set of equations below predicted the best tensile, burst, tear indices, and specific light scattering coefficient for handsheets prepared without removing the shives.

\[
\begin{align*}
\text{Tensile} & = 26.3 - 0.033(CSF) + 0.227(LF) - 2.13 \cdot \ln (1 + SC) \quad (4.29) \\
\text{Tear} & = 1.91 + 0.021(CSF) + 0.077(LF) - 7.9 \times 10^{-5}(LF)^2 \quad (4.30) \\
\text{Burst} & = 2.05 - 0.004(CSF) + 0.023(LF) + 0.05(SC) \quad (4.31) \\
\text{SSC} & = 649 - 0.205(CSF) - 17.1 \cdot \ln (1 + SC) \quad (4.32)
\end{align*}
\]

where:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile index</td>
<td>tensile</td>
<td>$N \cdot m/g$</td>
</tr>
<tr>
<td>Tear index</td>
<td>tear</td>
<td>$mN \cdot m^2/g$</td>
</tr>
<tr>
<td>Burst index</td>
<td>burst</td>
<td>$kPa \cdot m^2/g$</td>
</tr>
<tr>
<td>Scattering coefficient</td>
<td>SSC</td>
<td>$m^2/kg$</td>
</tr>
<tr>
<td>Canada Standard Freeness</td>
<td>CSF</td>
<td>$ml$</td>
</tr>
<tr>
<td>Long fibre content</td>
<td>LF</td>
<td>%</td>
</tr>
<tr>
<td>Shive content</td>
<td>SC</td>
<td>%</td>
</tr>
</tbody>
</table>

41
The comparison between the model predictions and literature data [51] are shown in Figure 4.8. It was found that the model can predict the burst, tensile indices and scattering coefficient fairly well, but the prediction of tear index is poor. This may be due to the complexity of tear index itself or because of the different intrinsic fibre properties from different wood species. It should be noted that the chip fractions had a major influence on the pulp and handsheet properties. Inclusion of the chip fractions into the model may improve the model predictions.

Figure 4.8: Burst and tensile index, model prediction vs measurement.
4.3 Simulation Results and Discussions

4.3.1 Operating conditions

The models presented in the previous section have been put together according to the structure shown in Figure 4.3 to represent the refining process. In this section, we show the simulation results obtained for our case study of the refining process. The normal operating conditions of the primary and secondary refiners are listed in Table 4.2 and 4.3 respectively.

It should be pointed out that the operation constraints may vary depending upon the refiner type (i.e. twin, double or single discs) and manufacturer. In this process, the twin refiners are used for both primary and secondary refining. A twin refiner is essentially a combination of two single disc refiners. Side A and side B can each be considered as a single disc refiner. The design parameters of a single refiner are listed in Table 4.4.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Symbol</th>
<th>Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial friction coefficient ( )</td>
<td>$\mu_r$</td>
<td>0.25</td>
</tr>
<tr>
<td>Tangential friction coefficient ( )</td>
<td>$\mu_t$</td>
<td>0.75</td>
</tr>
<tr>
<td>Inlet radius of refining zone (m)</td>
<td>$r_1$</td>
<td>0.514</td>
</tr>
<tr>
<td>Outlet radius of refining zone (m)</td>
<td>$r_2$</td>
<td>0.762</td>
</tr>
<tr>
<td>Bars per unit length of arc (m$^{-1}$)</td>
<td>$n$</td>
<td>100</td>
</tr>
<tr>
<td>Single disc refiner</td>
<td></td>
<td>$h=1, a=4$</td>
</tr>
</tbody>
</table>

Table 4.4 Design parameters of the refiner.
### Table 4.2 Operating conditions of primary refiner.

<table>
<thead>
<tr>
<th>Process Conditions</th>
<th>Symbol</th>
<th>Lower bound</th>
<th>Typical Value</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput (kg/s)</td>
<td>$F_c$</td>
<td>3.00</td>
<td>3.79</td>
<td>4.89</td>
</tr>
<tr>
<td>Dilution water (kg/s)</td>
<td>$F_{dw}$</td>
<td>6.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilution water temperature (°C)</td>
<td>$T_d$</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry bulk density (kg/m$^3$)</td>
<td>$\rho$</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content</td>
<td>$M$</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chip temperature (°C)</td>
<td>$T_i$</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet consistency (%)</td>
<td>$C_i$</td>
<td>27.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing pressure (kPa)</td>
<td>$CP$</td>
<td>6895</td>
<td>8724</td>
<td>9653</td>
</tr>
<tr>
<td>Motor load (kW)</td>
<td>$ML$</td>
<td>12000</td>
<td>12500</td>
<td>13000</td>
</tr>
<tr>
<td>Enthalpy of steam @refining pressure</td>
<td>$H_s$</td>
<td>2739</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor efficiency</td>
<td>$\eta$</td>
<td>90%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy loss</td>
<td>$\epsilon$</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer screw speed (rpm)</td>
<td>$TS$</td>
<td>25</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Disc rotational speed (rpm)</td>
<td>$\omega$</td>
<td>1800</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_2$</td>
<td>10.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_3$</td>
<td>1562.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refining temperature (°C)</td>
<td>$T_o$</td>
<td>143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refining pressure (kPa)</td>
<td>$P_{ref}$</td>
<td>381</td>
<td>389</td>
<td>399</td>
</tr>
</tbody>
</table>
Table 4.3 Operating conditions of secondary refiner.

<table>
<thead>
<tr>
<th>Process Conditions</th>
<th>Symbol</th>
<th>Lower bound</th>
<th>Typical Value</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rate (kg/s)</td>
<td>$F_{src}$</td>
<td>3.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilution water (kg/s)</td>
<td>$F_{sr dw}$</td>
<td>1.7</td>
<td>1.73</td>
<td>1.76</td>
</tr>
<tr>
<td>Dilution water temperature (°C)</td>
<td>$T_{sr d}$</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet consistency (%)</td>
<td>$C_{sri}$</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet stock temperature (°C)</td>
<td>$T_{sri}$</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing pressure (kPa)</td>
<td>$C P_{sr}$</td>
<td>5860</td>
<td>6205</td>
<td>6550</td>
</tr>
<tr>
<td>Motor load (kW)</td>
<td>$M L_{sr}$</td>
<td>8000</td>
<td>9000</td>
<td>10000</td>
</tr>
<tr>
<td>Enthalpy of steam @ refining pressure</td>
<td>$H_{sr s}$</td>
<td>2736</td>
<td></td>
<td></td>
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<tr>
<td>Energy loss</td>
<td>$\epsilon_{sr}$</td>
<td>5%</td>
<td></td>
<td></td>
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<tr>
<td>Motor efficiency</td>
<td>$\eta_{sr}$</td>
<td>90%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disc rotational speed (rpm)</td>
<td>$\omega_{sr}$</td>
<td>1800</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>$k_{sr 2}$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_{sr 3}$</td>
<td>1562.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refining temperature (°C)</td>
<td>$T_{sro}$</td>
<td>142</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refining pressure (kPa)</td>
<td>$P_{sref}$</td>
<td>381</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3.2 Primary Refiner

4.3.2.1 Effect of flow rate and temperature of dilution water on the outlet consistency

The effects of flow rate and temperature of the dilution water on the refiner outlet consistency are shown in Figure 4.9. The simulation results indicate that the higher the temperature of the dilution water, the more steam is generated in the refiner and this will lead to an increase in the outlet consistency, Figure 4.9(a) and 4.9(b). On the other hand, if the dilution water flow rate is increased, less steam is generated and the outlet consistency decreases. The refining consistency is an important variable which affects the refining action. Although it is difficult to measure the refining consistency on-line, the outlet consistency is a good indication of it. It is important to note that when the dilution water temperature increases from 40 to 97°C, the outlet consistency only increases from 35.0 to 37.5%. In a pulp mill, the normal range of dilution water temperature is between 70 °C to 80 °C, thus the outlet consistency will be affected by about 0.5%. On the other hand, the dilution water

![Figure 4.9: Outlet consistency and steam flow rate vs. temperature and flow rate of dilution water at constant specific energy.](image)
flow rate is a very effective variable in controlling the refining consistency. As shown in Figure 4.9(c), when the dilution water flow rate increases from 5.0 kg/s to 7.5 kg/s, the outlet consistency decreases from about 43% to 33% and the steam flow rate decreases from 4.0 kg/s to 3.73 kg/s.

4.3.2.2 Effect of transfer screw speed and closing pressure on motor load, specific energy, inlet consistency, outlet consistency, residence time and refining intensity

The refiner motor load, specific energy, inlet consistency, outlet consistency, residence time and refining intensity corresponding to different transfer screw feeder speeds (production rate) and closing pressures are shown in Figure 4.10.

Both closing pressure and transfer screw feeder speed affect the motor load. An increase in either closing pressure or screw speed leads to an increase in motor load, Figure 4.10(a).

Figure 4.10(b), illustrates that at a given screw speed (production rate), an increase in the closing pressure increases the specific energy. While at a given closing pressure, increasing the screw speed (production rate) decreases the specific energy, although the motor load has increased. By increasing the screw feeder speed (30–35 rpm) the production rate increases (3.6–4.2 kg/s) relatively more than the motor load (10–11 MW). The net effect is a decrease in the specific energy (2.78–2.6 MJ/kg).

If the dilution water flow rate is constant, an increase in production rate increases the inlet consistency. Under a constant inlet consistency, an increase in closing pressure causes more steam generation and consequently the outlet consistency is increased, as shown in Figures 4.10(c) and 4.10(d).

A recent study [71] on refining intensity and pulp quality in high consistency chip refining indicated that the residence time of the material in a chip refiner is a significant parameter in the determination of the refining intensity, and consequently in the determination of the final pulp quality for a given application of the energy.

It can be seen from Figures 4.10(b) and 4.10(f) that when the closing pressure is increased at constant screw feeder speed, the specific energy increases but the refining intensity decreases. Increasing the specific energy by decreasing the transfer feeder speed leads to an increase in refining
Figure 4.10: Effect of transfer screw feeder speed and closing pressure on (a) motor load; (b) specific energy; (c) inlet consistency; (d) outlet consistency; (e) residence time; (f) refining intensity.
intensity. This can be explained by taking the residence time into consideration. When increasing the closing pressure, the increase in specific energy is outweighed by the increase in residence time, resulting in a decrease in refining intensity.

A contour plot of specific energy and refining intensity is shown in Figure 4.11. To achieve a desired specific energy, one can operate the refiner at different production rates and closing pressures. Given the required specific energy and refining intensity, the operating point can be found from the intersection of the equal-specific energy and equal-refining intensity lines. This should be applied cautiously, since too high a closing pressure may result in plate clashing.

![Contour plot of specific energy and refining intensity](image)

**Figure 4.11**: Contour plot of specific energy and refining intensity. — : equal-specific energy line (MJ/kg); - - - : equal-refining intensity line (kJ/kg).
4.3.2.3 Effects of the transfer screw speed and the closing pressure on the refining intensity and the pulp properties

The pulp properties (freeness, long fibre content and shive content) are affected by the operating conditions. The effect of transfer screw feeder speed and closing pressure on the freeness is shown in Figure 4.12(d). The pulp freeness decreases when the transfer screw feeder speed is decreased or when the closing pressure is increased.

![Figure 4.12: Effect of transfer screw feeder speed and closing pressure on (a) specific energy; (b) specific energy per impact; (c) specific refining power; (d) Canadian Standard Freeness; (e) long fibre; (f) shive content.](image)
Comparing the contour plot of specific energy and freeness in Figure 4.13, one can see that with the same specific energy a different freeness can be achieved with a different refining intensity. The same applies to the long fibre content and shive content.

\[ \text{Figure 4.13: Contour plot of specific energy and freeness vs. closing pressure and production rate.} \]

- - : specific energy (MJ/kg); - - - : freeness (mL).
4.3.3 Secondary refiner

The pulp from the primary refiner is sent to the primary cyclone where steam is separated from
the pulp. Although part of the water in the cyclone turns into vapour when the pressure is released
in the cyclone, the pulp consistency will not change very much through the cyclone. According to
our calculations from typical operating conditions, the difference between the inlet and the outlet
consistency of a cyclone is less than one percent. Since there is no accumulation in the cyclone, the
feed rate to the secondary refiner can not be adjusted independently. Thus the operating variables for
the secondary refiner are then limited to the dilution flow rate and the hydraulic closing pressure.

4.3.3.1 Effect of dilution water flow rate and closing pressure on motor load, specific energy,
   inlet consistency, outlet consistency, residence time and refining intensity

The refiner motor load, specific energy, inlet consistency, outlet consistency, residence time
and refining intensity versus the dilution water flow rate and closing pressure are shown in Figure
4.14. Both motor load and specific energy increase with increasing closing pressure. The inlet and
outlet consistency change with the same trend. If the closing pressure is increased, the specific energy
increases and more steam is generated in the refiner. This leads to an increase in the outlet consistency.
Higher closing pressure leads to a longer residence time, which results in a lower refining intensity.

4.3.3.2 Effect of closing pressure and dilution water on pulp properties

The simulation results of refining intensity and pulp properties versus the closing pressure and
dilution water flow rate are shown in Figure 4.15. An increase in the closing pressure or a decrease
in the dilution water flow rate results in a decrease in the refining intensity and the specific refining
power. Lower refining intensity is beneficial to the fibre development. An increase in the closing
pressure lowers freeness, long fibre content and shive content.
Figure 4.14: Effect of dilution water flow rate and closing pressure on (a) motor load; (b) specific energy; (c) inlet consistency; (d) outlet consistency; (e) residence time; (f) refining intensity.
Figure 4.15: Effect of dilution water flow rate and closing pressure on (a) specific energy; (b) refining intensity; (d) Canadian Standard Freeness; (e) long fibre content; (f) shive content.
4.3.4 Simulation of handsheet properties

The effects of the primary variables (transfer screw feeder speed, closing pressure and dilution water flow rate) and disturbances (chip bulk density and chip moisture content) on the pulp properties and handsheet properties are summarized in Table 4.5. The change of handsheet properties as affected by transfer screw feeder speed and closing pressure are shown in Figure 4.16.

The simulation results in Table 4.5 show the trend of variations in manipulated variables, disturbances and pulp and handsheet properties. An increase in the transfer screw feeder speed or the chip bulk density leads to increases in freeness, long fibre content and shive content. Consequently, the burst, tensile and the scattering coefficient decrease. Variations in production rate either by manipulating the transfer screw feeder speed, or due to the variation in chip bulk density, produces large variations in pulp and handsheet properties. The closing pressure is an effective manipulated variable to control pulp quality. Dilution water flow rate, however, can only be used to tailor the pulp properties slightly. It may also be noted from Table 4.5 that the same magnitude of variation in operating conditions leads to very large variations in tensile and burst index, but relatively small variations in tear index and specific light scattering coefficient.

Table 4.5 Variations (%) in manipulated variables, disturbances and pulp and handsheet properties.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Ref.</th>
<th>Vari.</th>
<th>CSF</th>
<th>LF</th>
<th>SC</th>
<th>Burst</th>
<th>Tensile</th>
<th>Tear</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw feeder speed</td>
<td>30</td>
<td>+10</td>
<td>+8.6</td>
<td>+3.6</td>
<td>+25.1</td>
<td>-9.5</td>
<td>-8.0</td>
<td>+2.7</td>
<td>-3.1</td>
</tr>
<tr>
<td>Chip bulk density</td>
<td>100</td>
<td>+10</td>
<td>+8.6</td>
<td>+3.6</td>
<td>+25.1</td>
<td>-9.5</td>
<td>-8.0</td>
<td>+2.7</td>
<td>-3.1</td>
</tr>
<tr>
<td>Closing pressure</td>
<td>8274</td>
<td>+10</td>
<td>-4.5</td>
<td>-1.7</td>
<td>-33.7</td>
<td>+3.8</td>
<td>+6.0</td>
<td>-1.3</td>
<td>+2.2</td>
</tr>
<tr>
<td>Inlet consistency</td>
<td>27.2</td>
<td>+10</td>
<td>-6.9</td>
<td>-3.0</td>
<td>-5.9</td>
<td>+7.2</td>
<td>+4.5</td>
<td>-1.9</td>
<td>+1.8</td>
</tr>
</tbody>
</table>
Figure 4.16: Effect of transfer screw feeder speed and closing pressure on (a) tensile index, $N \cdot m/g$; (b) tear index $mN \cdot m^2/g$; (c) burst $kPa \cdot m^2/g$ and (d) specific light scattering coefficient $m^2/kg$. 
4.4 Summary

In this chapter, we have presented a mathematical model that relates the manipulated variables (transfer screw feeder speed, closing pressure and dilution water flow rate) of a refiner with the pulp properties (consistency, freeness, long fibre content and shive content) and the handsheet properties (burst, tensile, tear index and specific light scattering coefficient).

The refining mechanism is represented by the refining intensity and the average refining power. These two variables are calculated from the pulp residence time between the refiner plates, the number of impacts, and the specific energy. These variables depend upon the refiner design and operating conditions. The parameters used in the model depend upon the type of refiner and they can be calibrated from mill data. We finally present some simulation results for a 325 metric tons per day production line equipped with twin refiners. From these simulations, we have learned the following:

1. When the chip feed to the refiner is constant, increasing the hydraulic closing pressure increases the specific energy but decreases the refining intensity. This can be explained by taking the residence time into consideration. When increasing the closing pressure, the increase in specific energy is outweighed by the increase in residence time, resulting in a decrease in refining intensity.

2. Different combinations of production rate and closing pressure can lead to the same pulp freeness. The same applies to long fibre content and shive content. The model can be used to optimize the operation of a refiner according to quality requirements and costs.

3. For primary refiners, there are three operating variables: the transfer screw feeder speed, closing pressure, and dilution water. For secondary refiners only closing pressure and dilution water can be manipulated, although expensive variable speed refiners have an additional degree of freedom for pulp quality control.

4. It is also found that the closing pressure is an effective manipulated variable to control pulp quality. Dilution water flow rate on the other hand can only be used to tailor the pulp properties slightly.
Chapter 5

Pulp Screening and Reject Refining Process

5.1 Introduction

In this chapter, we present the mathematical models of the pulp processing part of a CTMP plant. Simulations of the effects of disturbances (feed stock consistency, freeness, shive content and fibre fractions) and operating conditions (screen reject rates and reject refiner specific energy) on the final pulp quality are performed and discussed.

In a CTMP plant, following chip refining, the plant comprises a series of unit operations aimed at enhancing and controlling pulp quality. These unit operations are latency chest to remove latency and to straighten fibres; screens to remove debris, shives, long stiff fibres and other undesirable materials; reject refiners to further refine debris and shives while fibrillating long stiff fibres; and/or cleaners to remove dirt, low specific surface fibres and heavy contaminants. The process flowsheet of our case study is illustrated in Figure 5.1. In this particular process, a two-stage, cascade screening system is used. The accepts from the primary screen are sent directly to the decker, and the secondary screen stage concentrates the shives rejected by the primary stage. The accepts from the secondary screen are recycled to the primary screen, while the rejects from the secondary screen are further treated via reject refining and reject screening. Cleaners are not used in this mill.

The objective of the work in this chapter is to develop a dynamic model for the pulp processing system and to study the interactions between the operation units and the effects of operating conditions on the final pulp quality. Pulp freeness, long fibre content and shive content are used to describe the pulp quality. Since pulp consistency has a particular effect on the operation of screens and reject refiner, it was also included in the model.
Figure 5.1: Flowsheet of the pulp screen and reject refining process in our CTMP plant.
This chapter is organized as follows. First, the dynamics of the pulp processing plant are discussed. Following that, the effect of the latency chest on the pulp properties is discussed and a model is proposed. Then modelling of the pulp screen is investigated. Finally, the effect of disturbances, screen reject rate and reject refiner specific energy are simulated. The simulation results are presented and discussed.

5.2 Mathematical Models

5.2.1 System dynamics

In the screening and reject refining process, there are surge tanks between the unit operations (Figure 5.1). Screening itself is a very fast process in comparison to the surge tank dynamics. When accept or reject valves are manipulated, the resulting stock flows responding to the valve setting can be described as a first order system with a minimal time delay. The time constant appears to be in the order of ten seconds [72]. The screen dynamics can be attributed to a combination of the response of the flow control valve and the effects of changes in fibre mat consistency or thickness at the reject side of the screen plate. The time constants of the tanks are of the order of ten minutes. It is thus appropriate to assume that the dynamics of the screens can be neglected when studying the dynamics of the whole pulp processing plant. Therefore, a steady-state model was used to represent each single screen, and the dynamics of the whole process is dictated by the tanks and transport delays in the pipes.

A tank with \( n \) inputs and \( m \) outputs is shown in Figure 5.2.
When modelling the tank, we assume perfect mixing in our tank model. Under this assumption, the total mass balance (for the general case with multiple inputs and multiple outputs) can be written as:

$$\frac{d\rho V}{dt} = \sum_{i=1}^{n} \rho_i \cdot F_{in,i} - \sum_{j=1}^{m} \rho \cdot F_{o,j}$$

(5.1)

**Total fibre balance:**

$$\frac{d\rho V \cdot C_o}{dt} = \sum_{i=1}^{n} \rho_i \cdot F_{in,i} \cdot C_{in,i} - \sum_{j=1}^{m} \rho \cdot F_{o,j} \cdot C_o$$

(5.2)

**Shive content:**

$$\frac{d\rho V \cdot C_o \cdot SC_o}{dt} = \sum_{i=1}^{n} \rho_i \cdot F_{in,i} \cdot C_{in,i} \cdot SC_{in,i} - \sum_{j=1}^{m} \rho \cdot F_{o,j} \cdot C_o \cdot SC_o$$

(5.3)

**And long fibre content:**

$$\frac{d\rho V \cdot C_o \cdot LF_o}{dt} = \sum_{i=1}^{n} \rho_i \cdot F_{in,i} \cdot C_{in,i} \cdot LF_{in,i} - \sum_{j=1}^{m} \rho \cdot F_{o,j} \cdot C_o \cdot LF_o$$

(5.4)

where:

- \( V \) is the volume of pulp stock inside the tank;
- \( F_{in} \) and \( F_o \) are the volumetric flow rates of stock;
- \( C_{in} \) and \( C_o \) are the consistencies;
$SC_{in}$ and $SC_o$ are the shive contents;

$LF_{in}$ and $LF_o$ are the long fibre contents;

There are very few studies concerning the freeness of pulp blends. According to results reported by Partanen and Koivo [73], the logarithm of the freeness can be used to model the relation between the freeness of a blend and the freeness of the pulps being blended. They used the following rule

$$\ln (CSF_{blend}) = \sum_{i=1}^{n} W_i \cdot \ln (CSF_i)$$

(5.5)

to relate the CSF of three TMP lines.

where $W_i$ is the weight fraction.

To investigate this further, we mixed pulps with freeness 200 ml and 500 ml from a CTMP process and tested for the freeness of the mixtures. The test results are shown in Figure 5.3. We plotted the test data and the calculation from equation 5.5. As can be seen from the plot, the calculation is in good agreement with experimental data over a wide freeness range. From the above equation, we can take the logarithm of the freeness as a variable and derive the unsteady-state equation for freeness as follows:

$$\frac{d \ln (CSF_o)}{dt} = \sum_{i=1}^{n} \frac{F_{in,i} \cdot C_{in,i}}{V \cdot C_o} (\ln (CSF_{in,i}) - \ln (CSF_o))$$

(5.6)

where $CSF_{in,i}$ and $CSF_o$ are the freeness of the different inlet pulp streams and the freeness of the outlet pulp respectively.

5.2.2 Latency chest

Pulp produced at high consistency refining conditions contains aggregates of fibres. If diluted with cold water at the refiner discharge, the fibres in these aggregates are frozen in a twisted, kinked, distorted shape. The cellulose in the distorted fibre is held in an elastically stressed condition by a rigid hemicellulose-lignin network and the pulp shows high freeness and poor physical properties.
If, on the contrary, the fibres are diluted at a temperature above 60°C in a dilute slurry, the lignin-hemicellulose structure softens and the stress in the cellulose, called latency, is removed. This results in a pulp showing lower freeness and higher strength than the cold-disintegrated pulps. In CTMP plants, a latency chest is usually located after the secondary refiner. Latency chests are designed to allow for a residence time of about 30 minutes and the temperature is maintained at about 75°C to facilitate latency removal. A minimum residence time of 20 minutes and temperature of 60°C [4] are required to achieve a complete latency removal. To achieve the dual objectives of long residence time and good mixing, baffles are usually put inside the chest to prevent by-pass, and agitation is applied to enhance mixing at the inlet of the chest. A typical design of a latency chest is depicted in

Figure 5.3: Freeness of the mixture of pulps with different freeness.

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Figure 5.4: The flow pattern inside a latency chest can be very complicated due to the mixing, plug flow, channelling and by-passing. However, to simplify the model, the stock flow in a latency chest can be considered as a perfectly mixed flow followed by a plug flow. The residence time associated with the perfect mixing and plug flow regions depend upon the design and operation of the latency chest. According to the mill experience, the ratio of mixing/plug flow volume is around 20/80 range. The model of a latency chest with respect to consistency, long fibre content and shive content is equivalent to a first order plus deadtime system.

As the main objective of a latency chest is to remove latency, special attention has to be paid to the modelling of pulp freeness. It was observed by Mohlin [74] that the drop in freeness was fairly constant for the TMP pulps having a freeness greater than 100 ml when latency is completely removed (see Figure 5.5). As such, with respect to pulp freeness, the latency chest can be modelled by the following equations:

For the perfectly mixed region:

\[
\frac{d \ln (CSF_{PM,o})}{dt} = \sum_{i=1}^{n} \frac{F_{in,i} \cdot C_{in,i}}{V_{PM} \cdot C_o} (\ln (CSF_{in,i}) - \ln (CSF_{PM,o})) \quad (5.7)
\]

for the plug flow region:

\[
CSF_{PF,o}(t) = CSF_{PF,i}(t - \tau) \quad (5.8)
\]
Figure 5.5: Freeness of cold-disintegrated and hot-disintegrated pulps.[74]

for the freeness drop:

$$CSF_{LC,o} = CSF_{PF,o} - CSF_{5}$$

where:

$CSF_{PM,o}$ is the output freeness from the perfectly mixed part of the latency chest;

$CSF_{PF,i}$ and $CSF_{PF,o}$ are inlet and outlet freeness of the plug flow part;

$CSF_{LC,o}$ is the freeness from the latency chest after the latency removal;

$CSF_{5}$ is a constant by which the freeness drops through the latency chest.

$\tau$ is the dead time associated with plug flow region.

5.2.3 Pulp screens

The purpose of screening is to remove undesirable materials such as shives, large fibre bundles, sand and grits. There are several types of screens currently used in pulp mills. The major types
are flat, rotary, centrifugal, and pressure screens. The mechanisms by which screens remove the unwanted materials from the pulp suspension are not fully understood. Nevertheless, there is a general agreement that separation in pulp screens is accomplished by the combination of two fundamental phenomena: barrier screening and probability screening [75]. In barrier screening, the size of the contaminants is larger than the screen plate orifices, and the screen behaves much as a sieve. In probability screening, the size of the contaminants is smaller than the openings on the screen plate, but some physical factors prevent the passage of these contaminants. Among the probability screening parameters cited in the literature the most common are: the angle at which the particles approach the screen plate apertures (critical angle), the force created by the difference in fluid velocities inside the screen (shear force), the movement of fibres inside the screen (fibre alignment), and the interaction of neighboring fibres (fibre mat) [76, 77]. However, models based on these parameters are extremely complex and calibration of the model parameters is difficult. Recently, some research has addressed the flow resistance of screen plate apertures [78] and the effect of fibre length on passage through narrow apertures [79].

In the following paragraphs, previous studies on pressure screen modelling are discussed and a mathematical model is proposed to predict the shive removal efficiency, consistency, and freeness of different streams from the operating conditions of a pressure screen.

5.2.3.1 Shive removal and fractionation

A schematic of a pressure screen is shown in Figure 5.6. A screen has four major flows: feed stock, dilution water, accept pulp, and reject pulp.

To characterize the performance of a screen, two parameters are commonly used. They are the ‘efficiency’, $E_s$, and the ‘reject rate’, $R_s$.

One definition of screen efficiency is the ratio of shives in the feed that passes to the reject stream.

$$E_s = \frac{F_r \cdot C_r \cdot SC_r}{F_f \cdot C_f \cdot SC_f}$$  \hspace{1cm} (5.10)
where:

\[ SC_r, SC_f \] are the shive contents in the reject and feed stock;

\[ F_r, F_f \] are the total volumetric flow rates of reject and feed stock;

\[ C_r, C_f \] are the consistencies of reject and feed stock respectively.

The reject rate is the overall ratio of the feed pulp that passes to the reject stream [80].

\[ R_s = \frac{F_r \cdot C_r}{F_f \cdot C_f} \]  \hspace{1cm} (5.11)

The relationship between efficiency and reject rate is used to assess the screen performance. A typical \( E - R_s \) curve is shown in Figure 5.7. A screen of good performance is one having a high efficiency at a low reject rate; that is, the maximum removal of shives with the minimum loss of good fibres.

![A schematic diagram of a pressure screen.](Image)
Two screen performance equations, each containing a single independent parameter, have appeared in the literature [81, 82]. They are the Kubat equation:

$$E_s = R_s^\beta$$  \hspace{1cm} (5.12)

and the Nelson equation:

$$E_s = \frac{R_s}{1 - \alpha + \alpha R_s}$$  \hspace{1cm} (5.13)

where:

$E_s$ is the shive removal efficiency;

$R_s$ is the reject rate;

$\alpha$ and $\beta$ are independent parameters called screen quotients.

The theoretical derivation of the above equations by Gooding and Kerekes [83] shows that these two equations are based on two different assumptions concerning the amount of mixing adjacent
to the screen plate in a pressure screen. Equation (5.13) results from the mixed flow model while
equation (5.12) results from the plug flow model. The two equations represent the two extreme cases
(perfect mixing and plug flow) and therefore define the boundaries within which a real screen works.
In the literature, equation (5.13) was widely used, however, Gooding and Kerekes [83] found that
the plug-flow model best represents what happens in a screen. We therefore decided to use equation
(5.12) to calculate the shive removal from reject rate.

The relationship between reject rate and the shive content can be represented as follows:

$$ R_{s}^{\beta_{SC}} = \frac{F_r C_r S C_r}{F_f C_f S C_f} $$

(5.14)

where $\beta_{SC}$ is the screen quotient for shives.

Although the above equations were developed for the shive removal efficiency in a pulp screen,
conceptually, they can also be used to describe the separation of different fibre fractions in a pulp
screen. The smaller and more flexible a fibre, the higher the probability it will pass through the slots
and go to the accept stream. The amount of fibres being rejected tends to increase with increasing
length and decreasing flexibility. Equation (5.12) is also used to calculate the long fibre yield of a
pulp screen. For long fibres, the equation relating reject rate to efficiency is:

$$ R_{s}^{\beta_{LF}} = \frac{F_r C_r L F_r}{F_f C_f L F_f} $$

(5.15)

where $\beta_{LF}$ is the screen quotient for long fibres.

As previously mentioned, the shives and long stiff fibres tend to be rejected, while the short and
flexible fibres pass more easily through the screen apertures. For a good performance screen, $\beta_{SC}$
will have a low value, close to zero, while the $\beta$ for short fibres and fines will be close to one. The
values of $\beta_{SC}$, $\beta_{LF}$ for any particular screen can be obtained from the fibre fractions in the reject
and feed streams in the screen tests.
5.2.3.2 Consistency changes through screening

Apart from shive removal and fibre fractionation, another variable of interest is the pulp consistency and how it changes through a screen. Gooding and Kerekes [84] have investigated the consistency drop and reject thickening of the pressure screen under different reject ratios. Their model is based on the passage ratio of fibres through an aperture. Before presenting the model, definitions of some special terms are needed and are provided below.

(1) The passage ratio $P$ is defined as the pulp consistency $C_s$ in the flow through a screen aperture, divided by the consistency $C_u$ in the flow immediately upstream of the aperture, (Figure 5.8).

$$ P = \frac{C_s}{C_u} $$  \hspace{1cm} (5.16)

![Figure 5.8: A section of screen plate in a pulp screen.](image)

(2) The ratio of reject consistency and feed consistency is a useful measure of thickening and is called the “reject thickening factor”, or $T_{rej}$.

$$ T_{rej} = \frac{C_r}{C_f} $$  \hspace{1cm} (5.17)

where $C_f, C_r$ are the feed and reject consistencies respectively.
(3) The “reject ratio” or $R_v$ is defined as the ratio of the volumetric flow rate of the reject stream, $F_r$, and the volumetric flow rate of the feed, $F_f$.

$$ R_v = \frac{F_r}{F_f} \quad (5.18) $$

(4) The “normalized consistency drop” $D$ is defined as

$$ D = \frac{C_f - C_a}{C_f} \quad (5.19) $$

where $C_a$ is the accept consistency and $C_f$ is the feed consistency.

Both a plug-flow model and a mixed-flow model have been developed by Gooding and Kerekes [84], but the authors pointed out that predictions are more accurate when the plug-flow model is used to simulate the consistency change through a screen.

The plug-flow model assumes no axial mixing in the screening zone. It does, however, assume perfect radial mixing between the rotor and the screen plate, and hence consistency is assumed uniform in the direction perpendicular to the screen plate. Thus the reject thickening factor and the consistency drop can be calculated [84]:

Reject thickening factor:

$$ T_{rel} = R_v^{(P-1)} \quad (5.20) $$

and consistency drop:

$$ D = \frac{R_v^P - R_v}{1 - R_v} \quad (5.21) $$
5.2.3.3 Freeness correlation

It is generally agreed that the fibre length and the bonding ability are the two most important intrinsic properties of CTMP pulp. The bonding potential mainly depends on the specific surface area of the fibres. Although pulp freeness is an empirical measure of the drainage of a pulp suspension, freeness is closely related to the fibre specific surface [41]. Freeness is easy to measure compared to specific surface, and on-line measurement of freeness is commonly used in the industry. So in addition to fibre fractions, freeness is one of the variables chosen to characterize the pulp properties in the screening process.

A model is needed to calculate the freeness of accept and reject stocks from the freeness of the feed stock and operating conditions of a screen. Since pulp freeness is not a conservative parameter as we discussed before, there is a lack of understanding of the mechanism behind the splitting or mixing of pulp stocks of different freeness. Only a few experimental works and empirical models have been reported in the literature. Hill et al. [85] showed that a simple relationship holds when the ratio of accept freeness to feed freeness is plotted against the screen reject rate as shown in Figure 5.9.

A linear relationship can be obtained from the data [85] as:

\[
\frac{CSF_a}{CSF_f} = 1 - 2.0 \times R_s
\]  

(5.22)

In the above equation, the accept freeness becomes negative when the reject rate is larger than , thus this linear equation only applied to low reject rates.

In order to predict the freeness ratio over a wider range of reject rates, we suggest the following relationship:

\[
\frac{CSF_a}{CSF_f} = e^{-\theta \times R_s}
\]  

(5.23)

Where \( \theta \) is a parameter. From the mill data, \( \theta \) was estimated to be 2.08. The predictions by equation (5.23) are compared with data we collected at our mill and literature data (Figure 5.9). Using the above equation, we can therefore predict the accept freeness from the feed freeness over a wider range of reject rates.
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Figure 5.9: Freeness ratio vs reject rate, 1: reproduced from [85]; 2: equation (5.22); 3: mill data; 4: equation (5.23) 5: literature data [86].

Figure 5.10: Calculated accept freeness versus measured accept freeness
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The predicted accept freeness and the data [87] are presented in Figure 5.10 and are in good agreement.

Now that we have developed a mathematical relationship between the freeness of the feed stock and the freeness of the accept stock at a given reject rate, we need a relationship between the operating conditions of a pressure screen and the freeness of the reject stock.

Partanen and Koivo [73] reported that the freeness of a pulp mixture from three production lines could be calculated using the following equation:

\[
\ln CSF_o = \left( \sum_{i=1}^{3} F_i \times C_i \times \ln CSF_{in,i} \right) / \sum_{i=1}^{3} F_i \times C_i
\]

(5.24)

where:

- \(CSF_{in,i}\) represents the freeness of production line \(i\);
- \(F_i \times C_i\) represents the fibre mass flow rate of production line \(i\);
- \(CSF_o\) represents the output freeness of the three production lines.

If it is assumed that the freeness of pulp streams into and out of a screen also follow this rule, the following equation can be derived.

\[
F_f \cdot C_f \cdot \ln CSF_f = F_a \cdot C_a \cdot \ln CSF_a + F_r \cdot C_r \cdot \ln CSF_r
\]

(5.25)

where:

- \(CSF_f, CSF_a, CSF_r\) are the freeness of the feed, accept and reject streams respectively;
- \(F_f, F_a, F_r\) are the stock flow rates of the feed, accept and reject streams respectively.

Combining equation (5.23) and equation (5.25) leads to the following expression between the reject freeness and the feed freeness:

\[
\frac{CSF_r}{CSF_f} = e^{8 \times (1 - R_a)}
\]

(5.26)
Figure 5.11: Calculated reject freeness vs. measured reject freeness.

The comparison between predictions from equation (5.26) and data from Hill [87] is shown in Figure 5.11. Once again, the prediction and the actual data of reject freeness are in good agreement. However, it should be pointed out that this set of data was obtained from a laboratory scale screen. The agreement for one type of screen does not necessarily apply to another type of screen.

5.2.4 Reject refiner

The reject refiner is an important unit of the pulp processing plant. The task of a reject refiner is to reduce shives and to further fibrillate long fibres. Beath [88] investigated the operation of a groundwood reject refining system and presented a simple relationship governing the reduction of the debris fraction in reject refining. His results were summarized as follows: (1) Due to electrical and mechanical energy losses, and loss of refining efficiency at wide plate clearance, there is an upper throughput tonnage beyond which debris reduction ceases; (2) Beyond that minimal point of specific energy, the rate of reduction of debris content per added unit of specific energy is directly proportional to the amount of debris present at any given moment. In other words, the specific energy required to reduce a unit mass of debris is inversely proportional to the debris concentration; (3) The slope
of the line is a measure of the efficiency with which the refiner reduces debris. Ryti, Paulapuro, and Nopanen [89] derived a model for the shive reduction in a reject refiner. The equation is as follows:

\[ \frac{SC_i - SC}{SC_i} = 1 - e^{-\frac{ML}{F}} \]  (5.27)

where \( SC \) is the shive content, \( SC_i \) is the shive content in the refiner feed, \( ML \) is the motor power, \( F \) is the flow of fibres and shives through the refiner and \( \alpha \) is a parameter. Equation 5.27 can be rewritten into the following form:

\[ SC = SC_i \cdot e^{-\alpha \cdot SE} \]  (5.28)

where \( SE \) is the specific energy.

Their model was verified with mill trials for a double-disc refiner with open discharge, and for a single-disc refiner with pressurized discharge. The model prediction had a good agreement with the measurement of shive reduction.

In many aspects, however, reject refiners are similar to main line refiners. The model we developed for the main refiners, which is based on the concept of specific energy and refining intensity, is used in our simulation to predict the pulp properties of the reject refiner from its operating conditions. With the main line refiner model, not only can the shive reduction be predicted, but also the long fibre reduction and freeness reduction can be predicted.

5.3 Simulations

Simulations of the behaviour of the screening and reject refining process of our CTMP plant have been performed. The screening system consists of a typical two-stage screening with one stage reject refining process and the production rate was about 325 \( BDMT/D \). The feed stock flow rate to the primary screens was about 5500 \( l/min \) during normal operation. A simplified flow sheet of the system is shown in Figure 5.1.
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Different simulations have been performed. First, a steady-state simulation of the primary screen was performed and the simulation results compared to mill data to validate the screen model. Then, dynamic simulations were carried out to investigate the impact of disturbances and operating conditions on the pulp processing plant behavior.

5.3.1 Steady-state simulation

Table 5.1 shows the agreement between the model predictions and the mill data and it appears that the model predicts the performance of the screen fairly well.

Table 5.1. Comparing mill data to simulation results of a primary screen.

<table>
<thead>
<tr>
<th></th>
<th>Feed</th>
<th>Accept</th>
<th>Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mill Data</td>
<td>Prediction</td>
<td>Mill Data</td>
</tr>
<tr>
<td>Freeness (ml)</td>
<td>111</td>
<td>43.4</td>
<td>41</td>
</tr>
<tr>
<td>Consistency (%)</td>
<td>4.22</td>
<td>2.43</td>
<td>2.88</td>
</tr>
<tr>
<td>Shive (%)</td>
<td>0.20</td>
<td>0.056</td>
<td>0.06</td>
</tr>
<tr>
<td>Long fibre (%)</td>
<td>46.4</td>
<td>27.9</td>
<td>20.3</td>
</tr>
</tbody>
</table>

5.3.2 Dynamic responses to disturbances

The major disturbances are the feed stock characteristics such as shive content, fibre fractions, freeness, and consistency. The dynamic responses to variations from the main line refiners and from the other production line have been investigated. The scenarios of the simulations are listed in Table 5.2 and the simulation results are presented below.
Table 5.2 Simulation of disturbances on pulp properties.

<table>
<thead>
<tr>
<th>Disturbances</th>
<th>Variables affected by the disturbances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shive content from main line refiner discharge.</td>
<td>Shive content in primary screen accept, primary screen reject, secondary screen reject and reject screen accept.</td>
</tr>
<tr>
<td>Pulp consistency from main line latency chest.</td>
<td>Consistency of primary screen accept, primary screen reject, secondary screen accept and reject screen accept.</td>
</tr>
<tr>
<td>Pulp consistency from main line latency chest.</td>
<td>Shive content in primary screen accept, primary screen reject, secondary screen reject and reject screen accept.</td>
</tr>
<tr>
<td>Pulp freeness from main line refiner discharge.</td>
<td>Pulp freeness of primary screen accept, primary screen reject, secondary screen reject and reject screen accept.</td>
</tr>
<tr>
<td>Shive content from the other line.</td>
<td>Shive content in primary screen accept, primary screen reject, secondary screen reject and reject screen accept.</td>
</tr>
</tbody>
</table>

5.3.2.1 Change in shive content from the secondary refiner

Figure 5.12 shows the dynamic response of the shive content to a step change in shive content from the main line secondary refiner discharge.

The system started from steady state. After 150 minutes, the shive content from the secondary refiner discharge had changed from 1.0% to 2.0%; the other operating conditions remained the same. As seen in Figure 5.12, the change in shive content showed up in the primary screen accept and reject after a delay of about 20 minutes because of the latency chest. The shive content in the primary screen accept increased from 0.20% to 0.39%, while the reject line shive content increased from 1.27% to 2.47%. The secondary screen reject showed an increase from 2.29% to 3.95% in shive content. Due to the transportation delays and the intermediate tanks, the response in shive content in the secondary screen reject was slow. The response in the reject screen accept was much slower than in the secondary screen reject because of the recycle in the reject refiner and reject screen loop. The reject screen accept took about 250 minutes to reach a new steady state.
Figure 5.12: Dynamic response in shive content in different streams to a step change in shive content from main line refiner discharge.
5.3.2.2 Change in consistency from the refined chest

Figure 5.13 shows the dynamic response to a change in consistency from the refined chest. When the consistency from the refined chest was changed by 0.5% from 4.5% to 5% at simulation time of 150 minutes, the consistency in the primary screen accept and reject started increasing after a delay of about 20 minutes. The consistency of the primary screen accept increased from 2.0% to 2.2%, and the consistency of the primary screen reject increased from 5.1% to 5.6%. The responses in the secondary screen and reject screen was slow because of the recycle loop; the accepts of the secondary screen and the reject screen took about 150 and 250 minutes respectively to reach the new steady state.

![Diagram showing dynamic response of consistency to a consistency change from the main line latency chest.](image)

**Figure 5.13:** Dynamic response of consistency to a consistency change from the main line latency chest.

The effect of consistency of the pulp stock on shive contents of pulp streams at different locations was simulated and is shown in Figure 5.14. When the consistency from the refined chest increased from 4.5% to 5.0% at simulation time 150 minutes, the effect on primary screen accept shive content
was almost unnoticeable. However, there was a slight change in the shive content of the primary screen reject. The shive content in the primary reject was 2.56% before the consistency change and increased to 2.63% after the consistency change. The shive content in the secondary reject increased from 3.79% to 3.86% after the consistency change.

![Figure 5.14: Effect of consistency on the shive contents at different locations.](image_url)

5.3.2.3 Change in freeness from secondary refiner

The dynamic response to a freeness change from the secondary refiner discharge is shown in Figure 5.15. Here we assume a step change in freeness from the secondary refiner after 150 minutes. The responses were quite similar to those of the shive content and consistency. This was because the dynamic behavior of the system was dominated by the intermediate tanks and transport delays. It should be noted that a step change of freeness of 20 ml from the secondary refiner caused a change of 56 ml in the primary screen reject and a change of 76 ml in the secondary screen reject. The freeness of the primary screen and reject screen accept change by 12 ml and 7 ml respectively.
In this simulation, only the open-loop performance of the process was studied. If we have control over the freeness out of reject refiner, the change in freeness from the reject screen accepts may be further reduced. The simulation shows that the pulp processing plant reduces the incoming pulp property variability.

5.3.2.4 Change in shive content from another line

The dynamic response of shive content in different pulp streams to a disturbance from another refiner line is shown in Figure 5.16.

A step change from 1% to 2% in shive content in the pulp from another production line (Figure 5.1) took place after 150 minutes. It can be seen that most shives were rejected by the secondary screen and treated in the reject refiner. The final pulp quality as indicated by the shive content in the primary and reject screen accept was barely affected; there was almost no change in the primary screen accept and a change of only 0.1% in the reject screen accept. It was also shown that the reject screen accept responded to the disturbance much slower than all the other streams. It took about

![Figure 5.15: Dynamic response to a step change in freeness from the main line refiner discharge.](image)

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150 minutes to reach a new steady state; this dynamics was mainly determined by the reject screen and reject refiner loop. When there was an increase in shive content from secondary screen reject, the higher shive content entered the loop and was carried around the loop before the reject refiner could reduce the shive content to a new steady state. In this simulation, again the open loop system was studied, that is we assumed that the operating conditions did not change when there was a shive content increase. With this open loop system, the worst scenario would be that shives were carried and accumulated along the loop because the reject refiner was not capable of reducing all the shives.

The dynamic response of consistency and freeness to a disturbance from another refiner line is similar to what has been shown for the shive content. Since the dynamics of the system is determined by the reject screen and reject refiner loop, the responses of shive content, long fibre fraction, consistency and freeness to a disturbance have a similar behaviour.

![Figure 5.16: Dynamic response of shive content in different streams to a disturbance from another line.](image-url)
5.3.3 Dynamic response to changes in operating variables

The effect of some of the operating variables on the shive content, long fibre fraction, freeness and pulp consistency in different streams have also been simulated. The scenarios simulated are listed in Table 5.3 and the simulation results are summarized below:

**Table 5.3** Simulation of operating conditions on the pulp properties.

<table>
<thead>
<tr>
<th>Disturbances</th>
<th>Variables affected by the disturbances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor load of reject refiner</td>
<td>Shive content before reject refiner, after reject refiner, reject screen accept and reject screen accept</td>
</tr>
<tr>
<td>Primary screen accept flow rate</td>
<td>Shive content in primary screen accept, primary screen reject, secondary screen accept, secondary screen reject and reject screen accept</td>
</tr>
</tbody>
</table>

5.3.3.1 Reject refiner specific energy

Figure 5.17 shows the shive content in pulp streams as affected by the reject refiner specific energy.

![Graph showing shive content in different streams as affected by specific energy of the reject refiner.](image)

**Figure 5.17:** The shive content in different streams as affected by the specific energy of the reject refiner.
At 150 minute time, there was a negative step change in the specific energy of the reject refiner from 3.9 to 3.4 MJ/kg. The shive content after the reject refiner immediately responded with a jump followed by a slow change. The effect was also seen in the reject screen rejects. More shives from the reject screen were recycled to the reject refiner. This effect kept growing since the system acted as a positive feedback system. In some cases, it would eventually reach a new steady state, but after a long time period. For this particular situation, it took about 150 minutes to settle. It should be noted that in some cases, the shives in the reject refiner and reject screen loop would build up. To solve the problem, we should either increase the specific energy of the reject refiner or decrease the reject rate of the reject screen. The latter approach would apparently deteriorate the final pulp quality since more shives would be accepted by the reject screen.

5.3.3.2 Primary screen accept flow rate

Figure 5.18 shows the shive content in different streams along the process when the primary screen accept flow rate was changed by 7.6% from 5400 to 5810 l/min at 150 minutes. In this

![Figure 5.18: Dynamic response of shive content in different streams to a step change in accept flow rate of primary screen.](image-url)

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simulation, the motor load of the reject refiner remained unchanged. It was shown that when the primary screen accept flow increased by 7.6%, the shive content in the accept stream increased from 0.2% to 0.22%. Although the shive content in the secondary screen reject increased from 2.3% to 3.1%, the total shive rejected by the secondary screens decreased by 5% from 1.64 to 1.56 kg/min because of the decrease in total reject flow. With the same energy application to the reject refiner, the shive content in the reject screen accepts was reduced from 0.41% to 0.36%.

It was found that the shive content in the final pulp, the primary screen accepts and the reject screen accepts, changed from 0.276% to 0.260% when the primary screen accept flow rate was increased by 7.6% from 5400 to 5810 l/min. It is an interesting finding that the same pulp quality can be achieved under different operating conditions. This warrants further studies on the optimization of the screening and reject refining systems.

5.4 Discussion

The simulations presented here were based on a pulp processing plant in a CTMP mill. However, different mills may have different configurations of screens and reject refiners. The simulation package developed here can easily incorporate any changes in the process configurations as well as changes in unit operations.

The responses of the process to typical variations in incoming pulp and changes in operating conditions have been simulated. Nevertheless, many other scenarios can be simulated with this simulator.

From the simulations, we learned that the proper operation of the reject screen and reject refiner, and a full coordination of reject screen and reject refiner are very crucial in controlling the final pulp quality of the process. As previously discussed, a low level of specific energy in the reject refiner would probably cause the shives to become a “dead load”. While we can decrease the reject rate of the reject screen to eliminate the problem, we would have to sacrifice pulp quality. On the other hand, a higher specific energy than necessary would both reduce the pulp strength and waste energy.
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We have learned from this work that in the operation of a screening and reject refiner process, localized control of each operation unit does not necessarily achieve good performance for the whole process. For example, increasing the screen reject rates produces cleaner pulp but at the cost of more stock being circulated through the process, or in other words, higher capacity screens, larger intermediate tanks and bigger pumps are needed. This means more capital cost and more energy consumption. Operating strategies often oppose cost reduction concerns and product quality requirements. Therefore an optimization of a process involves not only the material flow rates but also knowledge of how the properties of the product change as operating conditions are changed. The models in this work predict the pulp properties from the operating conditions and can be used in optimizing process settings and operations.

5.5 Conclusions

Mathematical models for the pulp processing process in a CTMP plant have been developed. In the models, pulp consistency, shive content, long fibre content and freeness are used to describe the pulp properties along the process. The dynamic responses to the variations in properties of pulps entering the process were simulated. In this process, the dynamics were dictated by the tanks, the transportation delays, and most importantly by the recycling loops. Simulations of the impact of the manipulated variables on the pulp properties exiting the process were also carried out. Under normal operation, a small change in consistency does not have a significant effect on the shive content, fibre fractions and freeness of the product from the process. But for the operation of the screens, consistency is an important variable which should be carefully controlled because a higher consistency may cause the screen to blind while a low consistency will reduce the screen efficiency. The reject rate of each screen should be used to control the final pulp properties; but in practice, it is fairly difficult to control them independently, they should be coordinated. The specific energy of the reject refiner is a critical control variable since it has the most important impact on the final pulp shive content.
Chapter 6

Hydrogen Peroxide Bleaching Process

6.1 Introduction

In the previous chapters, we have discussed the modelling and dynamic simulation of the chip pretreatment process, chip refining process and pulp processing process. In this chapter, we will present the modelling and dynamic simulation of a hydrogen peroxide bleaching process.

Pulp bleaching is the chemical treatment of wood fibres to increase pulp brightness by removal or modification of the light-absorbing lignin in the fibres while preserving pulp strength. Hydrogen peroxide ($H_2O_2$) is a common bleaching chemical used in the brightening of mechanical pulps, especially for bleaching to a high brightness [90]. Bleaching of mechanical pulps with hydrogen peroxide removes relatively little lignin in contrast to conventional bleaching agents used in the first stage of a chemical pulp bleaching plant. This factor is important in maintaining the desired high yield of mechanical pulp.

The primary objectives of a bleaching plant are high pulp brightness, high production rate, low operating costs and low environmental impact. The large number of variables and the high cost of mill or pilot plant trials are a few of the problems encountered when optimizing the operation of bleaching processes [91]. A dynamic simulator offers a good tool for testing new bleaching operations and for developing control strategies. Early attempts to model hydrogen peroxide bleaching of mechanical pulp were based on steady-state mass balances [92, 93]. In this work, we present a dynamic model of a 325 tons per day brightening plant. Mathematical models of the blend chest, presses, mixers and bleaching towers were developed based on unsteady-state mass balances. The flow patterns of the pulp stock in a bleaching tower were studied and modelled as a combination of continuous stirred tank reactors plus a plug flow reactor. A kinetic model of hydrogen peroxide bleaching was integrated
into the bleaching tower model. The effect of operating conditions and disturbances on the bleaching process performance were examined. The dynamic responses of the process to changes in chemical charge, incoming pulp properties and other variables as well as the interactions among the operation units were revealed via dynamic simulations. Based on the model we have developed, we have also studied different control strategies for the bleaching process.

6.2 The Hydrogen Peroxide Bleaching Process

There are different configurations of hydrogen peroxide bleaching processes. The most commonly used configurations in mechanical pulp mills are one-stage and two-stage bleaching processes. Our case study mill uses a one-stage hydrogen peroxide bleaching process to produce a high brightness (>75% ISO) mechanical pulp for certain grades of newsprint. Figure 6.1 shows a schematic diagram of the process.

Pulps from different pulping lines are blended at about 4% consistency with a chelating agent DTPA (diethylene-triamine penta-acetate) in a blend chest. Then the pulp stock is pumped to a twin wire press, where the pulp is dewatered to a consistency of about 25-30%. Filtrate from the twin wire press was used elsewhere in the process. After the press, the stock is delivered to a repulper and then to a high shear mixer where the bleaching chemicals are mixed with the stock flow. The bleaching chemicals consist of hydrogen peroxide, magnesium sulphate, sodium silicate, and sodium hydroxide. These chemicals are mixed in a cascade tank, prior to being added to the pulp stock. Five percent hydrogen peroxide on oven dry pulp is a typical charge, and its flow is adjusted according to the production rate. Once the pulp and bleaching chemicals are mixed, the stock is pumped to a bleach tower where the stock is retained for about two hours at a temperature of 60 °C. Afterwards, the bleached pulp is discharged and diluted to about 4% consistency in a dilution tank and the bleaching reactions are terminated by the addition of \( SO_2 \), bringing the \( pH \) of the pulp down to about five.
Figure 6.1: A simplified flowsheet of a hydrogen peroxide bleaching process.
6.3 Model Development

Many experimental studies have been carried out on the effect of operating conditions on the final pulp brightness in a peroxide brightening plant [94–96]. Residence time, peroxide charge, reaction temperature, inlet pH and stock consistency are generally recognized as the determinant operating conditions. To model the peroxide bleaching process, we need to select a set of variables which is pertinent to the description of the physical and chemical phenomena taking place in the process.

Pulp brightness is of course the most important variable when discussing the bleaching process. Changes in production rate resulting from variations in the stock flow rate and/or stock consistency affect the residence time in the bleaching tower as well as the chemical demand to achieve the desired brightness gain. Variation in the brightness of the pulp entering the bleach plant is a major disturbance to the operation of the plant. Pulp consistency, temperature, chemical charge and inlet pH values determine the bleaching reaction rate. It was therefore decided to include the variables shown in Figure 6.2 in the mathematical model of the brightening plant.

![Diagram of the bleaching process](image)

Figure 6.2: Process units and variables of a bleaching process.
6.3.1 Blend chest model

The blend chest is used to mix pulps from different production lines. The chelating agent DTPA is introduced into the chest to trap the metal ions which, otherwise, will cause peroxide decomposition. It was assumed that the chelate of the metal ions was achieved before the addition of hydrogen peroxide, thus the kinetics of the chelation process was not modelled. The blend chest can be modelled as a tank which has several input streams and one output stream. A blend chest can have as many inputs as the number of refiner lines, but here we only consider a tank with two inputs and one output. A schematic diagram of a blend chest is shown in Figure 6.3. We assume that the stock in the blend chest is perfectly mixed. DTPA addition accounts for about 0.01% of the total stock flow to the blend chest and therefore can be neglected in the mass balance. The total mass balance in the blend chest is therefore given by:

\[ \frac{d\rho \cdot V_{bc}}{dt} = \rho_1 \cdot F_{bc,1} + \rho_2 \cdot F_{bc,2} - \rho_0 \cdot F_{bc0} \]  

(6.1)

where \( V_{bt} \) is the volume of the pulp stock inside the tank.

![Figure 6.3: Input and output variables of the blend chest.](image-url)
As the consistencies are around 4%, we can assume that the densities of the input and output streams are the same and remain constant. Thus the mass balance can be simplified to:

$$\frac{dV_{bc}}{dt} = F_{bci,1} + F_{bci,2} - F_{bco}$$  \hspace{1cm} (6.2)

Denoting the incoming stock consistencies as $C_{bc1}$ and $C_{bc2}$, and the exiting stock consistency as $C_{bco}$, the mass balance on the fibres is given by:

$$\frac{dV_{bc} \cdot C_{bco}}{dt} = C_{bc1} \cdot F_{bci,1} + C_{bc2} \cdot F_{bci,2} - C_{bco} \cdot F_{bco}$$  \hspace{1cm} (6.3)

Substituting equation (6.2) into equation (6.3):

$$\frac{dC_{bco}}{dt} = \frac{F_{bci,1}}{V_{bc}} \cdot (C_{bc1} - C_{bco}) + \frac{F_{bci,2}}{V_{bc}} \cdot (C_{bc2} - C_{bco})$$  \hspace{1cm} (6.4)

When modelling a bleach plant, it seems natural to use brightness as a state variable. However brightness measurement suffers from the drawback of being dependent not only on the chromophore content but also on the physical structure of the pulp (i.e. the light scattering coefficient). Thus, instead of taking the pulp brightness as a state variable, we use light absorption and scattering coefficients as state variables to represent the optical properties of the pulp. From the light absorption coefficient and light scattering coefficient, the brightness of the pulp can be calculated. This will be discussed later in the chapter.

The effects of mixing of pulps with different absorption and scattering coefficients on the optical properties of the bleached pulp is not fully understood. In the work of Parsons [97], the author prepared handsheets from mixtures of various fractions of pulp in order to determine how the light scattering and light absorption coefficients of mixtures related to those of individual pulp fractions. It was found that the light scattering and light absorption values of mixtures of pulps or pulp fractions were additive. Robinson [98] also reported that the scattering and absorption coefficients of a mixture of different pulps were additive. Thus the light scattering and absorption coefficients of the pulp exiting the blend chest can be described by the following equations:

$$\frac{dK_{bco}}{dt} = \frac{F_{bci,1} \cdot C_{bc1}}{V_{bc} \cdot C_{bco}} \cdot (K_{bc1} - K_{bco}) + \frac{F_{bci,2} \cdot C_{bc2}}{V_{bc} \cdot C_{bco}} \cdot (K_{bc2} - K_{bco})$$  \hspace{1cm} (6.5)
where:

\[ K_{bc1}, K_{bc2}, K_{bco}, S_{bc1}, S_{bc2}, S_{bco} \] are the light absorption coefficients and light scattering coefficients of the two input pulp streams and the output pulp stream respectively.

**6.3.2 Twin wire press model**

A twin wire press is a dewatering device which removes water from pulp stock and increases the consistency of the pulp stock. Pulp dewatering is a fairly complicated process [99]. In a twin wire press there are a few operation variables which will affect the outlet consistency. The most important variables are press loading and inlet stock consistency. In this work, we assumed that the press loading was constant. By fitting the mill operating data, it was found that the effect of inlet consistency on the outlet consistency can be described using the following relationship:

\[ C_{twp} = \gamma_{twp} \cdot \sqrt{C_{twp1}} \]  

(6.7)

where \( C_{twp1}, C_{twp} \) are the consistencies of the inlet and outlet pulp respectively, and \( \gamma_{twp} \) is an efficiency coefficient. In this mill we studied, it was found that a value of 15 gave the best fit to the mill data.

It was assumed that the dewatering process in the press would not change the light absorption coefficient and scattering coefficient. The dynamics of the press can be represented by a time delay caused by the transportation of the pulp through the press. This delay is of the order of a few minutes and can be neglected when simulating the dynamic behaviours of the whole bleach plant.

**6.3.3 Mixer model**

In the bleaching process, a mixer brings the pulp stock together with bleaching chemicals and water. Uniform distribution of chemicals in the pulp stock is critical for bleaching effectiveness. The
unique rheology of pulp stock makes it difficult to quantitatively describe the extent of mixing [100]. In this work, the mixing process was assumed to be perfect and instantaneous. A mixer is illustrated in Figure 6.4. The inlet streams are the pulp stock, chemical solution and mill water. Since the mixing process is assumed to be instantaneous, a steady-state mass balance is used to model the mixer. Once again, assuming the densities of the input and output streams are the same and remain constant, the total mass balance is given by:

\[ F_{\text{mixo}} = F_{\text{mix1}} + F_{\text{mix2}} + F_{\text{mix3}} \]  

(6.8)

the consistency can be calculated as follows:

\[ C_{\text{mixo}} = \frac{F_{\text{mix1}} \cdot C_{\text{mix1}} + F_{\text{mix3}} \cdot C_{\text{mix3}}}{F_{\text{mixo}}} \]  

(6.9)

and the hydrogen peroxide concentration is calculated from the following equation:

\[ [H_2O_2]_{\text{mixo}} = \frac{F_{\text{mix2}} \cdot [H_2O_2]_{\text{mix2}}}{F_{\text{mixo}}} \]  

(6.10)

the chemical charge in terms of percentage on oven dry fibres is obtained from the following equation:

\[ CC = 0.1 \times \frac{F_{\text{mix2}} \cdot [H_2O_2]_{\text{mix2}} \cdot W_{H_2O_2}}{\rho \cdot F_{\text{mix1}} \cdot C_{\text{mix1}}} \]  

(6.11)

where \( W_{H_2O_2} \) is the molecular weight of \( H_2O_2 \) which is 34 g/mol.

\( \rho \) is the fibre density.
The mixer residence time is in the order of seconds and although the reactions start in the mixer, we can consider that all the reactions take place in the bleaching tower from a modelling point of view. Thus, we assumed that variables such as light absorption and light scattering coefficients remain constant through the mixer.
6.3.4 Bleach tower model

6.3.4.1 Flow pattern

The bleaching tower is a key unit operation when modelling the bleaching plant. In order to model the dynamics of a bleaching tower, it is necessary to know the flow pattern of the pulp stock inside the tower. The flow pattern not only determines the residence time distribution of the reacting materials but also controls the effectiveness of the bleaching reaction.

Most of the research on the flow pattern and retention time of a bleaching tower have been directed towards conventional, kraft pulp, bleaching towers. Many researchers have used a plug flow model for their simulations [101–104], giving a pure time delay response. Here, deviations from plug flow are caused by a number of factors, including channeling, axial mixing, and radial variations in flow velocity. Mixing also occurs at the top and bottom of the towers due to the presence of impellers and/or rakes in these zones. For controller design, first order plus delay transfer functions have also been used to characterize dynamics of the key process variables, such as consistency, Kappa number, and brightness [105].

The flow behaviour in a bleaching tower can be approximated by a number of models [106]. Wang et al [107] have examined three cases. The first model uses a number of continuous stirred tank reactors (CSTR) in series to model the response measured for the tower. The second model uses a single CSTR followed by a plug flow reactor (PFR) to model the flow. The third model, CSTRS-PFR-CSTRS, combines a number of CSTRs before and after a plug flow reactor. In this latter case, the number of CSTRs and the PFR residence time can be varied to model a range of tower responses. That model gives a better agreement with experimental retention time distributions than the first two models. Wang et al found that with different consistencies, as much as 20% of residence time of the tower can be modelled as perfect mixing. The residence time modelled by perfect mixing and plug flow models at different consistency ranges is shown in Table 6.1.

Most of the recent mechanical pulp bleaching plants using hydrogen peroxide as a bleach agent operate at a 20% consistency or higher [94]. Apart from a little mixing at the inlet and outlet
Table 6.1 Residence time of perfect mixing and plug flow at different consistency ranges.

<table>
<thead>
<tr>
<th>Consistency %</th>
<th>Perfect mixing %</th>
<th>Plug flow %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-5</td>
<td>15-20</td>
<td>80-85</td>
</tr>
<tr>
<td>10-20</td>
<td>7-20</td>
<td>80-93</td>
</tr>
<tr>
<td>&gt;20</td>
<td>&lt;10</td>
<td>&gt;90</td>
</tr>
</tbody>
</table>

portion of the retention tower, the pulp stock is virtually in a state of plug flow inside the tower. Therefore, to model the dynamics of a retention tower with high consistency, the retention tower can be represented by a CSTR followed by a PFR and followed by a second CSTR. The flow pattern in a bleaching tower can be studied from a tracer response. The combination of CSTRs and PFR was chosen so that the model had the same mean residence time and variance as the experimental tracer response curve. In this simulation, we assumed that 90% of the residence time is in plug flow as the consistency is over 20%.

6.3.4.2 CSTR

An illustration of a CSTR or PFR with the input and output variables are shown in Figure 6.5.

![Figure 6.5: The retention tower with the input and output variables.](image)

For the mixing part of the tower, the total mass balance is given by:

\[
\frac{d\rho V}{dt} = F_{bt1} \cdot \rho_1 - F_{bto} \cdot \rho
\]  

(6.12)
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for consistency:

\[
\frac{dC_{bt}}{dt} = \frac{F_{bt1}}{V} \cdot \rho_1 (C_{bt1} - C_{bt})
\]  \hspace{1cm} (6.13)

for the light scattering coefficient:

\[
\frac{dS_{bt}}{dt} = \frac{F_{bt1} \cdot C_{bt1} \cdot \rho_1}{V \cdot C_{bt} \cdot \rho} (S_{bt1} - S_{bt})
\]  \hspace{1cm} (6.14)

for the light absorption coefficient:

\[
\frac{dK_{bt}}{dt} = \frac{F_{bt1} \cdot C_{bt1} \cdot \rho_1}{V \cdot C_{bt} \cdot \rho} (K_{bt1} - K_{bt}) - r
\]  \hspace{1cm} (6.15)

and for hydrogen peroxide concentration:

\[
\frac{d[H_2O_2]}{dt} = \frac{F_{bt1}}{V_{cstr}} ([H_2O_2]_{bt1} - [H_2O_2]_{bto}) - \Psi
\]  \hspace{1cm} (6.16)

where:

- \( V \) is the volume of the bleach tower described by the CSTR model, \( m^3 \).
- \( r \) is the rate of decrease of absorption coefficient, \( m^2/kg \cdot s \).
- \( \Psi \) is the reaction rate of hydrogen peroxide, \( mole/l \cdot s \).

6.3.4.3 PFR

Most of the retention tower can be modelled as a plug flow reactor. The total mass balance is:

\[ F_{bt1} = F_{bto} \]  \hspace{1cm} (6.17)

for consistency:

\[
\frac{\partial C_{bt}}{\partial t} = - \frac{\partial (v \cdot C_{bt})}{\partial z}
\]  \hspace{1cm} (6.18)
for scattering coefficient:

\[
\frac{\partial S_{bt}}{\partial t} = -\frac{\partial (v \cdot S_{bt})}{\partial z}
\]  

(6.19)

for light absorption coefficient:

\[
\frac{\partial K_{bt}}{\partial t} = -\frac{\partial (v \cdot K_{bt})}{\partial z} - r
\]

(6.20)

and for hydrogen peroxide concentration:

\[
\frac{\partial [H_2O_2]}{\partial t} = -\frac{\partial (v \cdot [H_2O_2])}{\partial z} - \Psi
\]

(6.21)

where:

\( v \) is the velocity the pulp slurry flowing in the tower, m/s.

\[
v = \frac{F_{bt1}}{A_{bt}}
\]

(6.22)

\( A_{bt} \) is the cross sectional area of the tower, m²

\( z \) is the position of the pulp slurry in the tower, m.

Equations (6.18) to (6.21) are two dimensional, partial differential equations with respect to the operating time, \( t \), and the position, \( z \).

By a transformation in time [108], so that the new time represents the time elapsed after the velocity front has passed the point \( z \), one obtains:

\[
t' = t - \frac{z}{v}
\]

(6.23)

Equation (6.18) to (6.21) become:

\[
C_{bt0}(t) = C_{bt1}(t) \cdot U(t')
\]

(6.24)
\[ S_{bt0}(t) = S_{bt1}(t) \cdot U(t') \]  

\[ K_{bt0}(t) = K_{bt1}(t) \cdot U(t') - \int_0^t r \cdot d\bar{t} \]  

\[ [H_2O_2]_o(t) = [H_2O_2]_1(t) \cdot U(t') - \int_0^t \Psi \cdot d\bar{t} \]

where \( U(t') \) is a delay function.

If we assume the height of the retention tower described by the plug flow model is \( L \), denoting the residence time described by plug flow model as \( t_p = \frac{L}{\bar{v}} \), then equations (6.24) to (6.27) become:

\[ C_{bt0}(t) = C_{bt1}(t - t_p) \]  

\[ K_{bt0}(t) = K_{bt1}(t - t_p) - \int_0^{t_p} r \cdot d\bar{t} \]  

\[ [H_2O_2]_o(t) = [H_2O_2]_1(t - t_p) - \int_0^{t_p} \Psi \cdot d\bar{t} \]

6.3.4.4 Kinetic model

The most important aspect in modelling a bleaching tower is the knowledge of bleaching reaction kinetics. There have been numerous studies of bleaching of mechanical pulps with alkaline hydrogen peroxide in which the resulting brightness of pulps is reported as a function of time and reagent concentration. Been [109] presented a new kinetic model for the alkaline peroxide brightening of mechanical pulp which is based on hydroxide and peroxide anion concentrations in the fibre wall. It is a good model to represent what is happening at the fibre level but not suitable for our simulation.
at the process level. Lundqvist [110], Moldenius [111] and Allison [112] have derived empirical expressions to relate chromophore concentration to reaction time. Most of these kinetic models have the following format.

\[
r = \frac{dK}{dt} = -k \cdot [H_2O_2]_{TOT}^a \cdot [OH^-]^b \cdot K^n
\]  

(6.31)

The difference is in the rate constant \(k\) and order constants \(a, b\) and \(n\).

Moldenius' [111] kinetic model is used to describe the hydrogen peroxide bleaching of mechanical pulps. The kinetic model is given by the following expression:

\[
r = \frac{dK}{dt} = -k \cdot [H_2O_2]_{TOT}^{0.67} \cdot [OH^-]^{0.23} \cdot K^{2.2}
\]  

(6.32)

where:

\(K\) = light absorption coefficient at 457 nm, \(m^2/kg\).

\(t\) = bleaching time, \(s\).

\([H_2O_2]_{TOT} = [H_2O_2] + [OOH^-] = \text{sum of undissociated and dissociated peroxide, mole/l.}\)

\([OH^-] = \text{hydroxide ion concentration, mole/l.}\)

\(k = \text{kinetic rate constant } (m^2/kg)^{-1.2}(\text{mole/l})^{-0.9}(s)^{-1}.\)

The effect of temperature on the kinetic rate constant is given by the Arrhenius equation:

\[
k = A \cdot e^{-E/(R \cdot T)}
\]  

(6.33)

where:

\(A = \text{pre-exponential factor, } (m^2/kg)^{-1.2}(\text{mole/l})^{-0.9}(s)^{-1}.\)

\(E = \text{activation energy, } J/mole.\)

\(R = \text{ideal gas constant, } J/(mole \cdot K).\)

\(T = \text{absolute temperature, } K.\)
6.3.4.5 Stoichiometry

In addition to the kinetic relationships, the stoichiometry of the bleaching reaction must be known. The bleaching stoichiometry describes how much peroxide is consumed to achieve a certain change in the light absorption coefficient. Moldenius [90] found that the stoichiometry was independent of pulp consistency and peroxide charge. It has also been shown that the stoichiometry is independent of the bleaching temperature up to 70 °C. His results were reproduced in Figure 6.6, in which the decrease in light absorption coefficient, $-\Delta K_{457}$, was plotted against the consumption of peroxide.

For our simulation, the stoichiometry coefficients were obtained by fitting a second order polynomial to the curve shown in Figure 6.6. The stoichiometry was represented as following:

$$\Psi = \psi_1 + \psi_2 \cdot r + \psi_3 \cdot r^2$$

(6.34)

The kinetic model predicts the light absorption coefficient, residual hydrogen peroxide and alkali from the process variables, temperature, chemical charge, residence time in the tower, and pulp

![Figure 6.6: Decrease in light absorption coefficient ($-\Delta K_{457}$) versus peroxide consumption ($-\Delta H_2O_2$), from Moldenius [113]](image-url)
consistency during bleaching. From the light absorption and light scattering coefficients, the pulp brightness can be calculated. The next section discusses how to calculate the brightness.

6.3.4.6 Correlations between absorption coefficient and brightness

To define the brightness of pulps, two terms are defined by the International Standards Organization. They are the reflectance factor $R$ and the intrinsic reflectance factor $R_\infty$. The reflectance factor $R$ is defined as the ratio, expressed as a percentage, of the radiation reflected by a body to that reflected by a perfect reflecting diffuser under the same conditions. The intrinsic reflectance factor $R_\infty$ is defined as the reflectance of a layer or pad of the material thick enough to be opaque.

The ISO brightness [114] is defined as the diffuse blue reflectance factor, that is, the intrinsic reflectance factor measured at an effective wavelength of 457 nm with a reflectometer having specific characteristics.

To predict the brightness of a pulp, a relationship between the light absorption coefficient and brightness is needed. The Kubelka-Munk equation [98] is used for this purpose. It provides a relationship between the absorption coefficient $K$, the scattering coefficient $S$, and the reflectance $R_\infty$:

$$R_\infty = 1 + \frac{K}{S} - \left[ \frac{2K}{S} + \left( \frac{K}{S} \right)^2 \right]^{\frac{1}{2}}$$ (6.35)

The ISO brightness is calculated from the light absorption and light scattering coefficients using the above equation. As for the light scattering coefficient, the same values can be used for unbleached and bleached pulp. This assumption is based on the reasoning that processes such as bleaching and dyeing change the light absorption coefficient but not the scattering coefficient [115]. Allison and Graham [112] found that peroxide bleaching has little effect on the light scattering coefficient. Average scattering coefficient values generally increased by 5% after peroxide treatment in their experiments. Polcin and Rapson [116] and Gellerstedt et al [117] have also reported very small increases in light scattering when pulps were bleached.
6.3.6 Dilution tank model

Following the bleaching tower, the bleached pulp is diluted to about four percent consistency using white water, and the bleaching reactions are terminated by the introduction of $SO_2$, bringing the pH of the pulp to about five. The dynamics of the dilution tank are similar to that of the blend chest, the model (Equation 6.1–6.6) developed for the blend chest was used to represent the dilution tank.

6.4 Simulations

A one-stage hydrogen peroxide brightening plant in our case study pulp mill was simulated. The modules used to represent the bleach plant are shown in Figure 6.7:

![Diagram of bleach plant modules](image)

**Figure 6.7:** Modules connected to represent the bleaching plant to be simulated.

The tank module was used to calculate the dynamics of the mixing of different streams while the mixer module was used to represent the instantaneous mixing of pulp streams and chemical solutions and to calculate the initial chemical concentrations of the bleaching reaction. The CSTR module and a PFR module were used to represent the bleaching tower.
The steady-state values of the variables used for the simulations, and the bleaching kinetic parameters obtained from the literature [90] are listed in Table 6.2.

The effects of typical disturbances on the bleaching plant have been studied. Four disturbances - brightness of incoming pulp, consistency of incoming pulp, chemical charge and production rate - were chosen as examples. In the dynamic simulations, one of the most important output variables is the pulp brightness after the bleaching tower. Thus, bleached pulp brightness responses to different disturbances are presented and discussed below:

6.4.1 Effect of incoming pulp brightness

Figure 6.8 shows the effect of a 10% change in brightness from 52.5% to 57.5% in one of the pulp streams entering the blend chest. The response in brightness of the pulp out of the blend chest was a first order response as expected. It took about 20 minutes to reach the new steady state in the blend chest. The change in brightness then appeared in the brightness of the pulp exiting the bleaching tower after a delay of approximately 100 minutes which was due to the plug flow of the pulp stock inside the tower. It took about 140 minutes to reach the new steady state in the bleaching tower and the final brightness out of the bleach tower increased from 74.2 to 77.0 ISO.
## Table 6.2 Scaled steady-state values used for simulations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp stock to blend chest</td>
<td>$F_{bc1}$</td>
<td>3226</td>
<td>L/min</td>
</tr>
<tr>
<td>Pulp stock to blend chest</td>
<td>$F_{bc2}$</td>
<td>3226</td>
<td>L/min</td>
</tr>
<tr>
<td>Pulp consistency to blend chest</td>
<td>$C_{bc1}$</td>
<td>3.5</td>
<td>%</td>
</tr>
<tr>
<td>Pulp consistency to blend chest</td>
<td>$C_{bc2}$</td>
<td>3.5</td>
<td>%</td>
</tr>
<tr>
<td>Scattering coeff. to blend chest</td>
<td>$S_{bc1}$</td>
<td>45</td>
<td>m²/kg</td>
</tr>
<tr>
<td>Absorption coeff. to blend chest</td>
<td>$K_{bc1}$</td>
<td>9.5</td>
<td>m²/kg</td>
</tr>
<tr>
<td>Pulp brightness to blend chest</td>
<td>$R_{bc1}$</td>
<td>52.5</td>
<td>ISO</td>
</tr>
<tr>
<td>Chemical flow from cascade tank</td>
<td>$F_{m2}$</td>
<td>183</td>
<td>L/min</td>
</tr>
<tr>
<td>Stock flow to the bleach tower</td>
<td>$F_{btl}$</td>
<td>900</td>
<td>L/min</td>
</tr>
<tr>
<td>Pulp consistency in bleaching tower</td>
<td>$C_{bto}$</td>
<td>25%</td>
<td>%</td>
</tr>
<tr>
<td>Residence time in CSTRs</td>
<td>$t_{CSTR}$</td>
<td>10</td>
<td>min</td>
</tr>
<tr>
<td>Residence time in PFR</td>
<td>$t_{PFR}$</td>
<td>100</td>
<td>min</td>
</tr>
<tr>
<td>Bleaching temperature</td>
<td>$T$</td>
<td>60</td>
<td>°C</td>
</tr>
<tr>
<td>Stock flow to the dilution tank</td>
<td>$F_{bto}$</td>
<td>5829</td>
<td>L/min</td>
</tr>
<tr>
<td>Pulp consistency in dilution tank</td>
<td>$C_{dto}$</td>
<td>4.5</td>
<td>%</td>
</tr>
<tr>
<td>Pulp brightness out of retention tower</td>
<td>$R_{bt}$</td>
<td>74.5</td>
<td>ISO</td>
</tr>
<tr>
<td>Activation energy</td>
<td>$E$</td>
<td>45</td>
<td>KJ/mole</td>
</tr>
<tr>
<td>Pre-exponential factor</td>
<td>$A$</td>
<td>$9.77 \times 10^5$</td>
<td>(m²/kg)⁻¹·² (mole/l)⁰·₉ (s)⁻¹</td>
</tr>
</tbody>
</table>
In the practical world, the brightness of the pulp from the refining process does not change as a series of well defined step changes. A more realistic scenario is shown in Figure 6.9. We took mill data of pulp brightness as a typical input brightness to the blend tank. The simulation shows that the high frequency variations of brightness in the incoming pulp were attenuated by the mixing effects in the blend chest and bleaching tower. However, the low frequency, high magnitude fluctuations proceeded through the process and were reflected in the bleached pulp.

Figure 6.8: Response to brightness step change in the incoming pulp.
Figure 6.9: Response to variations in incoming pulp brightness.
6.4.2 Effect of incoming consistency

The effect of change in incoming pulp consistency was studied and is presented in Figure 6.10.

Starting from steady state, the consistency of one of the pulp streams entering the blend tank decreased from 3.5% to 2.5%. If all of the other operating conditions were kept constant, the resulting chemical charge to the fibres would increase, leading to an increase in final pulp brightness. This is caused by more hydrogen peroxide reacting with the chromophore component in the fibres. However, in practice, the chemical flow rate is adjusted according to the production rate and the chemical charge is maintained constant.

Figure 6.10: Response to step changes in incoming pulp consistency.
6.4.3 Effect of chemical charge

In a bleaching plant, the chemical charge is often used to control the final pulp brightness. An increase in chemical charge results in higher initial concentration of hydrogen peroxide in the bleaching tower, resulting in higher brightness if the temperature and reaction time remain the same. When the chemical charge was decreased by 17% from 3.0 to 2.5%, the brightness after the bleaching tower increased by about 7.0% from 75 to 70 ISO. (Figure 6.11)

![Figure 6.11: Effect of chemical charge on the final pulp brightness.](image-url)
6.5 Control of the Bleaching Process

A bleaching plant represents one of the areas with the highest potential for loss of profit in a modern pulp mill. Overcharging of chemicals and poor control during a grade change can be extremely costly. However, off-spec product and operating costs can be greatly reduced using modern sensors and advanced control strategies.

A literature search revealed that many articles have been published on the control of kraft bleaching plants in general [118, 105, 119–122], but little work on the control of peroxide bleaching plant has been reported during the last decade [96]. A major cause was the difficulty involved in measuring and controlling all the variables in a bleaching plant. Complicated relationships between chemical charge, temperature, and retention time exist and these factors combine to influence brightness development.

The mathematical models and the dynamic simulation that we have presented have been used to compare the performance of existing control strategies and to try new ones. A good control system should maintain the final brightness constant, despite changes in initial pulp brightness and variations in production rate and consistency.

Different control strategies exist in the industry. In some mills, a ratio control loop is used to manipulate the chemical flow rate to the mixer according to the production rate. Figure 6.12 illustrates one way of implementing such a strategy. Other alternatives exist and are well documented [123]. This control strategy is based on the assumption that there is no variation in incoming pulp brightness and no change in the operating conditions of the bleaching tower, such as residence time and temperature. This simple control strategy works well as long as the initial pulp brightness remains relatively constant and the residence time in the tower is long enough for the reaction to be completed.

We simulated such a control strategy and the results are shown in Figure 6.13. It can be seen that when there was a variation in the incoming pulp brightness, the final pulp brightness also varied since the ratio control loop can only compensate for production rate variations.
Figure 6.12: Schematic of a ratio control strategy: the chemical flow rate is controlled according to production rate.
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Figure 6.13: Pulp brightness with ratio control.
Another way of controlling brightness is by implementing a feedback loop based on after tower brightness measurements. These measurements may come from manual laboratory tests or from an on-line brightness sensor. The measurements are compared to the brightness set point and the chemical charge is adjusted by the operators accordingly. This practice, however, possesses the inherent problem of destabilizing the system because of the long time delay in the bleaching tower. To illustrate this problem, we simulated a feedback control system where pulp brightness was the controlled variable and the chemical charge was the manipulated variable. The results are shown in Figure 6.14. To make the system stable, a small proportional gain and a large reset time had to be used here. It is quite common to see this loop tuned for a very large gain margin because of the long time delay in the tower, leading to a sluggish response. Delay compensation should be used as long as a good estimate of the tower residence time is available.

Figure 6.14: Brightness feedback control.
The control system performance can be significantly improved when all or some disturbances are measured on-line. In particular, when the incoming pulp brightness can be measured, a feedforward loop can be used. A feedforward control strategy is shown in Figure 6.15. From the model that we have developed for the bleaching tower, it is possible to calculate the chemical to fibre ratio required to reach the brightness set point after the tower for a given incoming brightness, temperature and residence time. The residence time is estimated from the pulp flow rate and tower design. The predicted ratio is sent to the ratio controller as the set point. The actual chemical to fibre ratio is calculated from the chemical concentration and flow rate, and pulp stock consistency and flow rate. Figure 6.16 shows the results of the feedforward control strategy:
Figure 6.15: feedforward and feedback control of pulp brightness.
Figure 6.16: The disturbance of incoming pulp brightness can be eliminated by the feedforward control system.
It can be seen that even with large variations in incoming pulp brightness, the final pulp brightness was stabilized around the set point. However, it is well known that a feedforward controller can only eliminate the effects of measured disturbances, providing a perfect process and disturbance model. In reality, the process is time-varying and there may be a mismatch between the process and the model. Under this circumstance, a feedforward controller can not fully eliminate the effects of the measured disturbances. For the disturbances which are not measured, the feedforward controller cannot cope with such disturbances. For example, Figure 6.17 shows the ineffectiveness of the feedforward controller to compensate for a slow drift in the temperature measurement.

![Graphs showing pulp brightness variations](image1)

Figure 6.17: Without a feedback control loop, the feedforward control itself can not cope with the slow drift in temperature measurement.
To compensate for disturbances which cannot be measured and to compensate for the model mismatch, it is common to add a feedback control loop. The feedback controller measures the final pulp brightness and makes minor adjustments to the chemical to fibre ratio (see Figure 6.15, dotted line). Figure 6.18 shows that the final pulp brightness is brought back to the set point despite a slow drift in the bleach tower temperature measurement.

Figure 6.18: The feedback control system brought the bleached pulp brightness to the target value even with a drift in bleaching tower temperature measurement.
6.6 Conclusions

The objective of this work was to develop a dynamic model for a mechanical pulp brightening plant, to study the dynamic behaviours of the plant and to compare different control strategies. Through the analysis of the process unit operations, a mathematical model has been developed to represent the dynamic behaviour of the brightening plant. The input variables of the model include the brightness and consistency of the incoming pulp, concentration and flow rate of chemical solutions to the process, production rate and bleaching temperature. The output variables of main interest are the final pulp brightness and the chemical residuals in the bleached pulp stock. Using a dynamic simulator, dynamic simulations of the bleaching plant have been carried out. The dynamic responses were studied for step changes in incoming pulp brightness, incoming pulp consistency and the chemical charge. The responses exhibit approximately first order plus a pure time delay dynamics. The simulations also revealed the sensitivity of the final pulp brightness to different operating conditions and disturbances. It was found that the chemical charge is the most sensitive controlling variable, and the initial pulp brightness is the major disturbance. Based on the model for the bleaching process, we have studied different control strategies. A feedforward and feedback control system can compensate for the effect of the incoming pulp brightness variations and reduce the effect of immeasurable disturbances.

Due to the modular nature of the simulator, the effect of all the operating conditions and disturbances can be studied in a similar manner. The simulator can be easily modified to study different bleaching processes such as two-stage peroxide bleaching processes and to test some advanced control strategies for the bleaching process.
Chapter 7

Simulations of a CTMP Process

In this chapter, we integrate the models of the different parts of a CTMP plant. Based on this integrated model of the plant, various scenarios were simulated to investigate the effects of process disturbances and operating conditions on the performance of the plant.

7.1 The Overall Process Model

Figure 7.1 shows the block diagram of the simulation model of a CTMP plant. The model consists of refining, pulp processing and bleaching processes. The chip pretreatment process is considered the source of chip quality variations. In the refiners, chips are transformed into pulps and pulp properties are carried through the rest of the process. Handsheet properties were also predicted at different locations along the process. The process disturbances and the operating conditions are listed in Table 7.1

7.2 The Simulation Scenarios

Once we have the overall simulation model of the plant, different scenarios can be simulated. Table 7.2 lists some typical ones. Simulation results of different scenarios are presented and discussed below.

7.2.1 Scenario 1: Step change in chip moisture content

In this scenario, a step change of 3% in moisture content of the chips feeding to the primary refiner was initiated and the process responses to this change were investigated. Figure 7.2 shows the process response to the change. During this simulation, the dilution water flow rates to the two refiner stages were kept constant when the step change in chip moisture content occurred, thus the
chip moisture content directly affects the refining consistency. The decrease in refining consistency reduced the residence time of the stock inside refiners and lead to a higher refining intensity. As a result of the high refining intensity, the pulp freeness dropped by 2.5% after the refiners. The freeness of the primary screen accept, secondary screen rejects, reject refiner and reject screen accepts are also shown in Figure 7.2. Due to the dynamics of the tanks and transportation delays in screening and reject refining processes, the freeness of reject screen accepts reached a new steady state about four hours after the step change in chip moisture content occurred.

Figure 7.3 shows the responses of the pulp and handsheet properties to the step change in chip moisture content. The pulp freeness, long fibre content and shive content from the decker are shown on Figure 7.3(b), (c) and (d). Tensile, tear, burst indices and scattering coefficient are shown on
Table 7.1 The process disturbances and the operating conditions

<table>
<thead>
<tr>
<th>Disturbances</th>
<th>Operating variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chip refiners</strong></td>
<td></td>
</tr>
<tr>
<td>Chip moisture content</td>
<td>Closing pressure</td>
</tr>
<tr>
<td>Chip density</td>
<td>Chip feeder speed</td>
</tr>
<tr>
<td>Dilution water temperature</td>
<td>Dilution water flow rate</td>
</tr>
<tr>
<td><strong>Pulp processing</strong></td>
<td></td>
</tr>
<tr>
<td>Other production line</td>
<td>Screen feed flowrate</td>
</tr>
<tr>
<td>Pulp freeness</td>
<td>Screen accept rate</td>
</tr>
<tr>
<td>Shive content</td>
<td>Feed stock consistency</td>
</tr>
<tr>
<td>Consistency</td>
<td>Closing pressure of reject refiner</td>
</tr>
<tr>
<td><strong>Bleach process</strong></td>
<td></td>
</tr>
<tr>
<td>Inlet pulp brightness</td>
<td>Stock flowrate</td>
</tr>
<tr>
<td>Inlet consistency</td>
<td>Chemical flowrate</td>
</tr>
<tr>
<td>Inlet stock temperature</td>
<td>Steam flow rate</td>
</tr>
</tbody>
</table>

Figure 7.3(e), (f), (g) and (h) respectively. This scenario shows that in this pulping process it takes about one hour to see the effect of a change in the chip moisture content at the screen room and it takes about four hours for the process to settle down and reach a new steady-state.

7.2.2 Scenario 2: Step change in chip density

Figure 7.4 shows the responses to a step change of 4% in chip bulk density from the steaming vessel discharge. During the simulation, the chip feed transfer screw speed was kept constant, thus with a density increase, the production rate increased by the same percentage. With the same dilution water flow rate to the refiner, the refiner inlet consistency is increased. Assuming the closing pressure applied to both refiners was constant, then the total specific energy decreased when there was an increase in production rate. The decrease in specific energy lead to an increase in pulp freeness. Freeness of primary screen accepts, secondary screen rejects, reject refiner, and reject screen accepts are shown on the right side of Figure 7.4. As in the previous example, the freeness from the reject
Table 7.2 Typical scenarios of simulated.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cause</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Chip moisture content to primary refiner</td>
<td>Outlet consistency of primary and secondary refiners, consistency of latency chest, freeness of primary screen accepts, secondary screen rejects, reject refiner, and reject screen accepts, freeness, long fibre and shive content from decker, tear, tensile, burst and scattering coefficient of pulp from decker.</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Chip density</td>
<td>Production rate, primary refiner inlet consistency, total specific energy, freeness of primary screen accepts, secondary screen rejects, reject refiner, and reject screen accepts, freeness, long fibre and shive content from decker, tear, tensile, burst and scattering coefficient of pulp from decker.</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Total motor load</td>
<td>Secondary refiner outlet consistency, freeness of primary screen rejects, secondary screen rejects, reject refiner and reject screen accepts, freeness, long fibre content, shive content from decker and tensile index, tear index, burst index, and scattering coefficient</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Specific energy of first and secondary refiner</td>
<td>Freeness, long fibre content and shive content after refiners.</td>
</tr>
</tbody>
</table>

screen accepts reached the new steady state four hours after the step change in chip density from the steaming vessel.

Figure 7.5 shows the changes in pulp and handsheet properties when a step change in chip bulk density from the steaming vessel was simulated. Figure 7.5(b), (c), (d) show the freeness, long fibre, and shive content from decker respectively. Figure 7.5(e), (f), (g), (h) show tensile index, tear index, burst index, and scattering coefficient of the pulp from decker.
Chapter 7: Simulations of a CTMP Process

7.2.3 Scenario 3: Step change in total motor load

In this scenario, step changes of 10% in motor load for both refiners were introduced by increasing the hydraulic closing pressure at 100 minutes and their effects on the process were simulated. Some process variables are shown on Figure 7.6. The figures on the left show the primary and secondary refiner motor load, the outlet consistency, and the primary screen reject chest consistency. Here we assumed that the dilutions to both refiners and the dilutions to both primary and secondary screens were constant. Because of the increase in power consumed by the refiners, more steam was generated in the refiners and the outlet consistency from the refiners was increased. It was not straightforward as to why there was a valley on Figure 7.6(f). We traced down the variables around the secondary screens and found that at the time there was a decrease in freeness from primary screen rejects, there

Figure 7.2: Responses to a step change in chip moisture content.
was also an increase in consistency from primary screen reject chest. Since freeness of the primary screen reject is higher than the freeness from the other line, a higher consistency in the primary screen reject chest makes a higher freeness in the secondary screen supply chest. Thus the final freeness of secondary screen reject started to increase at about 190 minutes. The responses of reject refiner and reject screen accept were similar to that of secondary screen reject and were apparently caused by that same effect.

The pulp and paper properties are shown in Figure 7.7. There are a few things to be noticed here. First, it was found that the long fibre content after the screening and reject refining process did not change much although the total motor load and thus the total specific energy applied to the refiners increased. This was because the increase in refining consistency reduced the refining intensity, thus
Figure 7.4: Responses to a step change in chip density.

less reduction in long fibre content inside the refiners occurred. The second finding is that there was a peak in burst index response. This brings to our attention, two issues. First, in most mills, the pulp samples are taken once every two hours and handsheet properties are tested; any variations faster than this sampling frequency would be averaged out or missed. Secondly, after settling down, the new steady state value of burst index was very close to the burst index before the step change in total motor load; thus, if the pulp samples were taken just across this changing period, no variations would be observed. Dynamic simulation reveals such variations as in Figure 7.7(g). Therefore, on-line measurement of pulp properties such as freeness, long fibre content, and shive content will be useful for on-line prediction and control of handsheet properties.
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7.2.4 Scenario 4: The effect of specific energy split ratio between first and secondary refiners.

Stationwala, Miles and Karnis [124] found that in a two stage TMP system, above a certain minimum level, the combination of a relatively low first stage specific energy applied at high intensity, followed by second stage refining at low intensity, proved quite beneficial. Miles, May and Karnis [71] found that increasing the first stage refining intensity by reducing the consistency resulted in a significant decrease in the total specific energy needed for a given freeness. In other words, with the same specific energy, increasing the first stage refining intensity results in a decrease in pulp freeness. We have simulated this scenario in which first stage specific energy is decreased from 3.5 $MJ/kg$ to 2.5 $MJ/kg$ while second stage specific energy is increased from 3.5 $MJ/kg$ to 4.5 $MJ/kg$. The effect on the pulp properties are shown in Figure 7.8. Figure 7.8(a) shows the first and second stage

![Figure 7.5: Pulp and handsheet properties responding to a step change in chip bulk density.](image)
specific energy; (b) shows the change in pulp freeness. As can be see from the figures, when the split ratio of second stage specific energy versus first stage specific energy changes from 1 to 1.8, the pulp freeness changes from 156 to 92. Figure 7.8 (c) and (d) show the long fibre and shive content versus the specific energy split ratio. As seen from (c), increasing the first stage refining intensity reduces the long fibre content. This is consistent with the findings by Miles [71] and Miles and Karnis [125]. Those findings demonstrate that the rate of material breakdown increases with increasing refining intensity. Stationwala et al [124] found that an increase in refining intensity in the first stage also results in lower shive content for a given total specific energy. The simulation result has the same trend as their experimental result (Figure 7.8(d)).
7.3 Discussions

In this chapter, we have integrated the model for the entire CTMP plant and carried out simulations of some typical scenarios. These simulation studies have revealed some insights into process variations and process interactions. A simple example can be found in scenario 2 where there was a change in chip density. Different consequences can happen depending on how we operate the process. In our simulation, we assumed that all the operating conditions are kept constant except the chip density. Thus we saw a change in production rate and the first refiner inlet consistency. Total specific energy also changed due to the change in production rate. The final effect on the process was that higher freeness pulp was produced. However, if we could measure the chip density precisely and were aware of the change in chip density, we could change the screw feeder speed
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Figure 7.8: The effect of the first refiner specific energy and secondary refiner specific energy on the pulp properties accordingly to keep the production rate constant. Thus the process would be running at a constant state, producing pulp with constant quality.

Although we have only presented four scenarios here, various operation conditions for a CTMP plant can be tested with this dynamic simulator.
Chapter 8
Summary and Future Work

8.1 Summary

There has been a very rapid and substantial increase in the use of computer simulation in the pulp and paper industry in recent years. Most recently, dynamic simulation has been recognized as a valuable tool for process optimization, process control and operator training. In addition, stricter limits on pulp quality, higher energy costs, and tighter environmental regulations have stimulated the development of dynamic models for pulp and paper processes. The objective of this thesis was to develop mathematical models for a CTMP plant. The models were used to study the dynamics of the plant.

Four major areas of a CTMP plant were studied and modelled.

In the first part of this work, the variability of the chip properties along the chip pretreatment process in a CTMP plant was studied. We collected and analyzed chip samples from the case study mill. It was found that the chip presteaming bin attenuated the variations in chip density and chip moisture content. Large variations were introduced to chip density and moisture content in the press impregnator because of the mechanical treatment on chips and the chemical spray at the end of the press impregnator. More complicated chip deformation was observed in the press impregnator. Due to physical limitations, chip samples were not taken from the steaming vessel.

The refining process is very complex due to the interactions between the process variables. In the second part of this work, the effect of process variables on the operation of a refining process and the interactions between them was studied. The refining mechanism was characterized by the refining intensity and the specific refining power. A mathematical model was developed to relate the manipulated variables to the refining intensity and the specific refining power. These two variables were calculated from the residence time, the specific energy and the number of impacts the fibres
experienced inside a refiner. Empirical relations were developed to predict the pulp and handsheet properties from the operating conditions of a refiner. These equations related the specific energy, the refining intensity, the specific refining power, and the sulfonate content to the pulp properties such as freeness, long fibre content, shive content, and to the handsheet properties such as burst index, tensile index, and light scattering coefficient. Simulations were performed for a 325 tons/day refining process equipped with two stage twin refiners. The simulation results showed the effect of the different variables on the final pulp and handsheet properties. They were in good agreement with previous studies and mill data.

The aim of the third part of this thesis was to investigate the operation of a screening and reject refining system and to develop a mathematical model which could predict the performance of a screening and reject refining process in terms of shive removal efficiency and dynamics of the process. In the model, pulp consistency, freeness, and long fibre content were used to describe the pulp properties along the process. Since screening and refining are very fast processes compared to the surge tank dynamics, it was assumed that the dynamics of the screening and reject refining process were determined by hold-ups in tanks, delays in pipes, and the recycling of the pulp stock. Steady-state simulations were first performed to compare the predicted pulp properties to mill values. Dynamic simulations were then performed to study the transient behavior of the process. The responses of the process to typical variations in incoming pulp and changes in operating conditions were simulated. From the simulations, it was found that small variations in consistency did not affect fibre fractions or freeness of the product. It was also found that good coordination between the reject screen and the reject refiner were critical for the smooth operation of the system and to the control of the final pulp quality. Below a certain level of specific energy in the reject refiner, the shive concentration began to increase and could become dead load. Although reducing the reject rate of the reject screen could eliminate the problem, the pulp quality would have to be sacrificed. On the other hand, a specific energy higher than necessary would both reduce pulp strength and waste energy.

The objective of the fourth part of this work was to develop a dynamic model for a hydrogen peroxide bleaching process, to study its dynamic behaviour, and to compare different control
strategies. Through the analysis of the process operation units, mathematical models were developed to represent the bleaching plant. Using the models, dynamic simulations of the bleaching plant were carried out. The dynamic responses to step changes in incoming pulp brightness, incoming pulp consistency, and chemical charge were studied. Simulations also revealed the sensitivity of the final pulp brightness to different operating conditions and disturbances. It was found that the chemical charge was the most sensitive controlling variable and the initial pulp brightness was the major disturbance. Based on the model for the bleaching process, different control strategies for controlling the final pulp brightness were compared. A feedforward plus feedback control strategy both eliminated the incoming pulp disturbance and reduced the bleached pulp brightness variations caused by other disturbances.

Finally, we integrated the models of the different parts of the CTMP plant and investigated the effects of process disturbances, operating conditions on the performance of the plant. The overall dynamic behaviours of the plant were studied by simulating the change in chip properties and observing the change in final pulp properties. It was found that it takes about an hour before a change in input conditions to the refiners can be see at the screen room and it takes about four hours for the process to settle down to a new steady state. The effect of total motor load on both refiners was also simulated and pulp and handsheet properties were recorded along the process. Conventional two stage refining processes usually have more or at least the same energy applied on the first stage refiner. However, a few experimental studies [124, 125] showed that lower specific energy applied at high intensity in the first refining stage proved to be beneficial. At a constant total specific energy, pulp properties improved. Alternatively, if the same specific energy was applied to the secondary refining stage, total energy consumption could be reduced to achieve the same freeness level. We have simulated these conditions and found the results were consistent with the experimental findings.
8.2 Future Work

Mathematical models for a CTMP plant have been developed. Some dynamic simulations have been performed to show the effects of operating conditions and disturbances on the pulp properties. A few control strategies have been tried in simulations. Further work is required, in the following areas:

1. Mill data should be collected to tune the model parameters when using the model to simulate a particular mill;

2. The models should be incorporated into more user-friendly dynamic simulators, such as IDEAS, ROSE, etc, to be of practical use in control system design and operator training.

3. The models integrated with a dynamic simulator should be used to perform process optimization off-line or on-line.
Appendix A  Nomenclature

A  
    pre-exponential factor of Arrhenius equation \((m^2/kg)^{-1.2}(mole/l)^{-0.3}s^{-1}\)

A_{bt}  
    cross sectional area of bleach tower (m^2)

C_a  
    accept consistency of a pulp screen (%)

C_{bc1, bc2}  
    pulp stock consistency into blend chest (%)

C_{bc0}  
    pulp stock consistency out of blend chest (%)

C_{bt1}  
    pulp consistency into bleach tower (%)

C_{bt}  
    pulp consistency in bleach tower (%)

C_{bto}  
    pulp consistency out of bleach tower (%)

C_{chem}  
    chemical concentration (%)

CC  
    chemical charge of hydrogen peroxide (% on od pulp)

C_c  
    specific heat of chips (kJ/kg)

C_f  
    feed consistency of a screen (%)

C_i  
    refiner inlet consistency (%)

C_{m1,3}  
    pulp stock consistency and mill water consistency into mixer (%)

C_{mo}  
    pulp stock consistency out of mixer (%)

C_o  
    refiner outlet consistency (%)

CP  
    hydraulic closing pressure of a refiner (kPa)

C_r  
    reject consistency of a screen (%)

C_w  
    specific heat of water (kJ/kg)

CSF  
    Canadian Standard Freeness (ml)

CSF_a  
    freeness of accept of a pulp screen (ml)

CSF_f  
    freeness of feed of a pulp screen (ml)
CSF<sub>r</sub>  freeness of reject of a pulp screen (m<sub>I</sub>)

C<sub>s</sub>  pulp consistency in the flow through a screen aperture (%)

C<sub>SO<sub>3</sub></sub>  sulphonate content defined as per cent of weight of \(SO_3^-\) over weight of dry weight of wood

C<sub>twpi</sub>  pulp stock consistency into twin wire press (%)

C<sub>twpo</sub>  pulp stock consistency out of twin wire press (%)

C<sub>u</sub>  pulp consistency in the flow immediately upstream of the screen aperture (%)

D  normalized consistency drop of a pulp screen

E  activation energy (J/mole)

E<sub>s</sub>  shive removal efficiency of a screen (%)

e  refining intensity (kJ/kg)

\(\dot{e}\)  average refining power (kJ/kg·s)

F<sub>bci</sub>  pulp flowrate into blend chest (L/s)

F<sub>bco</sub>  pulp flowrate out of blend chest (L/s)

F<sub>bt1</sub>  pulp flowrate into bleach tower (L/s)

F<sub>bto</sub>  pulp flowrate out of bleach tower (L/s)

F<sub>c</sub>  chip flow rate from the steaming vessel to refiner (kg/s)

F<sub>dw</sub>  flow rate of dilution water to a refiner (kg/s)

F<sub>f</sub>  feed flow rate of a screen (L/s)

F<sub>m1,2,3</sub>  pulp stock, chemical solution and mill water flowrate into mixer (L/s)

F<sub>mo</sub>  pulp stock flowrate out of mixer (L/s)

F<sub>r</sub>  reject flow rate of a screen (L/s)

F<sub>sw</sub>  flow rate of seal water of a refiner (kg/s)

\([H_2O_2]_{m2}\)  hydrogen peroxide concentration into mixer (mole/l)
\[[H_2O_2]_{m0}\] hydrogen peroxide concentration from mixer (mole/l)
\[[H_2O_2]_i\] hydrogen peroxide concentration into retention tower (mole/l)
\[[H_2O_2]_o\] hydrogen peroxide concentration out of retention tower (mole/l)
\(H_w\) enthalpy of water (kJ/kg)
\(K\) light absorption coefficient at 457 nm (m²/kg)
\(k\) kinetic rate constant \(((m^2/kg)^{-1.2}(\text{mole/l})^{-0.9}(\text{min})^{-1})\)
\(K_{bc1,bc2}\) light absorption coefficient of pulp into blend chest (m²/kg)
\(K_{bc0}\) light absorption coefficient of pulp out of blend chest (m²/kg)
\(K_{bl}\) light absorption coefficient of pulp stock into bleach tower (m²/kg)
\(K_{bo}\) light absorption coefficient of pulp out of bleach tower (m²/kg)
\(LF\) long fibre content in pulp stock (%)
\(L_s\) latent heat of steam (kJ/kg)
\(M\) moisture content of wood chip (%)
\(ML\) motor load of a refiner (MW)
\(n\) number of bars per unit length of arc of refiner plate ()
\(N\) total number of bar impacts on a fibre ()
\(P\) passage ratio of a pressure screen ()
\(P_{ref}\) refining pressure (kPa)
\(r\) the rate of decrease of absorption coefficient in retention tower (m²/kg · s)
\(R\) ideal gas constant (J · mole⁻¹K⁻¹)
\(RPM_{sc}\) rotational speed of screw conveyor
\(R_s\) reject rate of a screen (%)
\(R_v\) reject ratio, reject volumetric flow over feed volumetric flow
\(R_{oo}\) the intrinsic reflectance factor
\( r_1, r_2 \) \hspace{1cm} \text{inlet and outlet radii of refining zone in a refiner}

\( S \) \hspace{1cm} \text{the light scattering coefficient (m}^2/\text{kg)}

\( \text{SC} \) \hspace{1cm} \text{shive content in pulp stock (%)}

\( \text{SC}_f \) \hspace{1cm} \text{shive content in a screen feed ()}

\( \text{SC}_r \) \hspace{1cm} \text{shive content in a screen reject ()}

\( \text{SE} \) \hspace{1cm} \text{specific energy of a refiner (kJ/kg)}

\( \text{S}_{bc1, bc2} \) \hspace{1cm} \text{light scattering coefficient of pulp into blend chest (m}^2/\text{kg)}

\( \text{S}_{bc0} \) \hspace{1cm} \text{light scattering coefficient of pulp out of blend chest (m}^2/\text{kg)}

\( \text{S}_{bt1} \) \hspace{1cm} \text{light scattering coefficient of pulp into bleach tower (m}^2/\text{kg)}

\( \text{S}_{bt0} \) \hspace{1cm} \text{light scattering coefficient of pulp out of bleach tower (m}^2/\text{kg)}

\( \text{Sr} \) \hspace{1cm} \text{light scattering coefficient of pulp in retention tower (m}^2/\text{kg)}

\( T \) \hspace{1cm} \text{absolute temperature (K)}

\( T_{dw} \) \hspace{1cm} \text{temperature of dilution water (°C)}

\( T_i \) \hspace{1cm} \text{temperature of chips to the refiner (°C)}

\( T_o \) \hspace{1cm} \text{average temperature inside the refiner (°C)}

\( T_{rej} \) \hspace{1cm} \text{reject thickening factor}

\( TS_{rpm} \) \hspace{1cm} \text{transfer screwfeeder rotational speed (RPM)}

\( t \) \hspace{1cm} \text{time (s)}

\( V_{bc} \) \hspace{1cm} \text{volume of blend chest (m}^3\text{)}

\( V_{cstr} \) \hspace{1cm} \text{volume of bleach tower represented by CSTR (m}^3\text{)}

\( v \) \hspace{1cm} \text{velocity of the pulp stock moving in retention tower (m/s)}

\( W_j \) \hspace{1cm} \text{weight fraction of fibres entering the blend}

\( z \) \hspace{1cm} \text{the position of the pulp stock inside bleach tower (m)}

\( \alpha, \beta \) \hspace{1cm} \text{screen quotient}
\( \theta \)  
screen freeness model parameter

\( \epsilon \)  
energy loss in the refiner(\%)

\( \eta \)  
motor efficiency (\%)

\( \rho \)  
density of pulp stock \((kg/m^3)\)

\( \tau \)  
residence time of stock inside a refiner (s)

\( \mu \)  
friction coefficient between pulp and refiner discs

\( \omega \)  
rotational speed of a refiner disc \((rad/s)\)

\( \gamma_{twp} \)  
model parameter of a twin wire press

\( \Psi \)  
the reaction rate of hydrogen peroxide \((mole/l \cdot s)\)
**Appendix B  Pulp and Paper Terminology**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauer McNett</td>
<td>The method for classification of pulp fibres by passing a sample through a series of standard screens with different size holes and determining the percentage retained on each screen.</td>
</tr>
<tr>
<td>Breaking Length</td>
<td>The length of a sheet of paper which would break of its own weight when suspended vertically.</td>
</tr>
<tr>
<td>Brightening</td>
<td>A term commonly used to describe limited bleaching of mechanical pulp.</td>
</tr>
<tr>
<td>Brightness</td>
<td>A measure of the whitness of paper as compared to a standard.</td>
</tr>
<tr>
<td>Consistency</td>
<td>Weight per cent for moisture free, or air dry fibres in a suspension of pulp fibres in water.</td>
</tr>
<tr>
<td>Decker</td>
<td>An apparatus for dewatering pulp by filtering the fibres out on a mesh covered drum. It generally consists of a vat, a cylinder mold and a couch roll from which stock is removed by a doctor.</td>
</tr>
<tr>
<td>Disc Refiner</td>
<td>A continuous refiner, in which refining is accomplished by passing the stock between grooved plates located on two discs moving one related to the other.</td>
</tr>
<tr>
<td>Fibre</td>
<td>The unit cell of plant growth.</td>
</tr>
<tr>
<td>Fiberizing</td>
<td>A process for the reduction of fibre aggregates to individual fibres from such sources as wood chips, pulp sheets dry broke, reclaimed paper stock and the like.</td>
</tr>
<tr>
<td>Fibrillation</td>
<td>The loosening of thread-like elements from the fibre wall.</td>
</tr>
<tr>
<td>Fibrils</td>
<td>Thread-like elements of the cell wall of cellulose fibre.</td>
</tr>
</tbody>
</table>
Freeness  A measurement of the rate with which water drains from a pulp suspension.
Canadian Standard Freeness (CSF) is a standard test.


Opacity  The degree of non-transparency of paper.

Oven Dry (OD)  Pulp or paper dried in an oven by a standard laboratory procedure to the point
where it contains no moisture. The term Bone Dry (BD) is commonly used
synonymously. Oven dry weight divided by 0.9 equals the air dry weight in
standard practice.

Screen Room  A common term for screening and cleaning department which usually follows
pulping operations.

S–factor  Specific surface of the 48/100 fibre fractions.

Shives  A small bundle of fibres that has not been separated completely in the pulping
operations.

Stock  A general term for a suspension of pulp fibre in water, normally implies a
consistency between 0.2% and 15%.

Tear Resistance  The force required to tear a paper sample under specified conditions.

Tensile Strength  The resistance to breakage of paper when subjected to a tension stress.

White Water  Abbreviated ww, a general term for water removed from a pulp suspension
and containing a small amount of fibre and/or additives. On a paper machine,
the excess water drained through the wire from the furnish. The use of the
term "white water" usually implies low dissolved solids content. Always
white when white paper is produced, it contains pigments when running
colours, and can be any colours.
Appendix C  Variability Analysis of the Chip Pretreatment Process in a CTMP Plant

C.1 Introduction

A mill trial was conducted to study the time characteristics of chip and pulp quality variations and to analyze the cause and effect relationships among chip quality variations, process operating conditions, and the pulp quality variations. The results led us to a better understanding of the chip pretreatment process and the effect of chip quality on the pulp properties produced from these chips. The data has been reported by Mr. Sharma [126] and his contribution to the mill trial is acknowledged.

C.2 Sampling and testing procedures

A simplified diagram of the CTMP process is shown in Figure C.1.

Chips were taken from three points along the process. They were:

![Diagram of the CTMP process with chip sampling locations](image)

**Figure C.1:** A chip pretreatment process and the chip sampling locations, (A) after chip silo; (B) presoaking bin; (C) after press impregnator; (D) after secondary refiner.
Due to the limitations of the process equipment, we could not take samples after the steaming vessel.

The chip samples were put into plastic bags and sealed immediately. Chip moisture content, chip wet and dry bulk density, chip thickness fractions were tested. The laboratory tests were conducted according to the standard CPPA testing procedures. Chip moisture was determined using CPPA test standard D.18H, “Quality of Pulpwood Chips”. Chip wet bulk density was determined using the CPPA test standard A.1H, “Basic Density of Wood”. Chip dry bulk density was calculated from wet bulk density and moisture data. Chip thickness fractions were tested based on the CPPA standard D.27H, “Sieve Analysis of Pulpwood Chips”. The chip thickness fraction <2mm, 2–4mm, 4–6mm, 6–8mm, and >8mm were reported.

C.3 Results and discussions

The data from the laboratory test of chip samples were presented in Figure C.2 to C.4.
Figure C.2(a) shows the moisture content of the chips from the chip silos. The average moisture content of the chips from the silos is 51.0% and the standard deviation of the moisture content is 2.1%. Figure C.2(b) shows the moisture content of the chips from the presteaming bin. The average value is 61.5% and the standard deviation is 1.4%. Figure C.2(c) shows the moisture content of the chips from the press impregnator. The mean value is 47.5% and the standard deviation is 2.4%.

Figure C.2: Chip moisture content along the process.
Figure C.3(a) shows the chip wet bulk density from the chip silos. The mean value is 253.1 kg/m$^3$ and the standard deviation is 13 kg/m$^3$. Figure C.3(b) shows the chip wet bulk density from the presteaming bin. The mean value is 324.1 kg/m$^3$ and the standard deviation is 12.3 kg/m$^3$. Figure C.3(c) shows the chip wet bulk density from the press impregnator. The mean value is 186.4 kg/m$^3$ and the standard deviation is 13.2 kg/m$^3$.

Figure C.3: Chip wet bulk density along the process.
Figure C.4(a) shows the chip dry bulk density from the chip silos. The mean value is 124.2 kg/m$^3$ and the standard deviation is 6.9 kg/m$^3$. Figure C.4(b) shows the chip wet bulk density from the presteaming bin. The mean value is 124.8 kg/m$^3$ and the standard deviation is 4.4 kg/m$^3$. Figure C.4(c) shows the chip wet bulk density from the press impregnator. The mean value is 97.7 kg/m$^3$ and the standard deviation is 4.3 kg/m$^3$.

**Figure C.4:** Chip dry bulk density along the process.
Appendix D  Calculation of Residence Time in a Chip Refiner

D.1 Introduction

When applying equations from reference [127] to calculate the residence time in a chip refiner, we noticed that a term for the specific heat of water was missing from some of the equations. To make sure that the equation for the calculation of the residence time was right, we checked all the derivations and simplifications of the equations. It was found that the missing term in the steam flow equation in a refiner does not affect the simplified equation for the calculation of the residence time.

D.2 Derivation

In [127], it was stated that in an open discharge refiner, back-flowing steam condenses on the cooler incoming materials, and as a result decreases the inlet consistency. If it is assumed that the materials are preheated in this way to the boiling temperature of water before refining energy is applied, then the amount of heat required per unit weight of dry wood is given by

\[ Q_B = H(T_B - T_1) + \left( \frac{1}{S} - 1 \right) (T_B - T_1) + \frac{1}{C_i} \left( \frac{S - C_i}{S} \right) (T_B - T_2) \]  

(D.1)

where:

- \( Q_B \) = energy of back flow steam per unit weight of dry wood (\( \text{L}^2/\text{t}^2 \))
- \( H \) = specific heat of wood (\( \text{L}^2/\text{t}^2 \text{T} \))
- \( T_B \) = boiling temperature at radius \( r_1 \), where application of refining energy begins (T)
- \( T_1 \) = initial temperature of chips (T)
- \( S \) = solids content of chips (fractional)
- \( C_i \) = nominal inlet consistency (fractional)
- \( T_2 \) = dilution water temperature (T)
In equation D.1, it was assumed by the authors that the specific heat of water is one. If the engineering units Kcal/kg °K or BTU/lb °F are used, that assumption is valid. However, if the SI units are to be used, the specific heat of water becomes 4.18 KJ/kg °K. Thus the equation should be written as follows to allow the use of any unit systems:

\[ Q_B = H(T_B - T_1) + \frac{1}{C_i} (T_B - T_1) + \frac{1}{C_i} \left( \frac{S - C_i}{S} \right) (T_B - T_2) \]  

(D.2)

where \( H_w \) = specific heat of water (L^2/t L^2 T).

Thus the inlet consistency \( C\) at start of refining zone \( r_1 \) becomes:

\[ C_1 = \left( \frac{1}{C_i} + \frac{1}{L} \left[ (T_B - T_i) \left( H + H_w \left( \frac{1}{S} - 1 \right) \right) + \frac{1}{C_i} (S - C_i)(T_B - T_2) \right] \right)^{-1} \]  

(D.3)

where \( L \) = latent heat of steam at the inlet pressure (ML^2/t^2).

The rate of steam production between \( r \) and \( r + dr \) is:

\[ e^{2\pi r dr} = \left[ \dot{m}_d H + \dot{m}_d H_w \left( \frac{1}{C} - 1 \right) \right] dt_s + m_s 2\pi L_r r dr \]  

(D.4)

where

\( e \) = rate of application of energy per unit area of refiner plate (M/t^3)

\( \dot{m}_d \) = mass flow of dry wood (M/t)

\( C \) = consistency at radius \( r \)

\( t_s \) = saturated temperature of steam at pressure \( p \) (T)

\( p \) = pressure at radius \( r \) (M/Lt^2)

\( m_s \) = rate of steam production per unit area of refiner plate (M/L^2 T)

\( L_r \) = latent heat of steam at radius \( r \) (i.e. pressure \( p \)) (ML^2/t^2)

This is a rearranged form of equation from [128].

\[ \left( 0.3 \dot{m}_d + \left( \frac{100}{C_1} - 1 \right) \dot{m}_d \right) dt + m_s L 2\pi r dr = e^{2\pi r dr} \]  

(D.5)
In [128], English units were used, thus equation (D.5) was valid.

If SI units are used in equation (D.4), i.e., $H_w \neq 1$, then the equation from [127] shown below should be modified as follows:

$$m_s = \frac{1}{L_r} \left[ e - \frac{\dot{m}_d}{2\pi r C} (1 + CH - C) k_3 \frac{dP}{dr} \right]$$

\hspace{1cm} (D.6)

The consistency in the refining zone:

$$\frac{dC}{dr} = \frac{2\pi r m_s C^2}{\dot{m}_d}$$

\hspace{1cm} (D.8)

would also be affected since $m_s$ is related to $H_w$ as shown in equation (D.7).

$m_s$ also appeared in the steam velocity gradient equation (equation (4) from [127]):

$$\frac{dU}{dr} = \frac{m_s}{2\rho \epsilon (s + g)} - \frac{k_1 U dp}{\rho dr} - \frac{U}{r} \left( \frac{2s + a + g}{s + g} \right) - \frac{U dc}{\epsilon dr}$$

\hspace{1cm} (D.9)

In [22], the change of pulp velocity across the refining zone was given by:

$$\frac{dv}{dr} = \frac{rw^2}{v} - \frac{\mu r}{\mu_1} \frac{E c(r)}{w(r_2^2 - r_1^2)} + \frac{b}{2} C f r_s(r) U^2(r) A p(r) \frac{c(r)}{v}$$

\hspace{1cm} (D.10)

In the equation (D.10), both $U(r)$ and $c(r)$ terms are dependent on $m_s$, thus they also depend on $H_w$.

In [26], it was assumed as a first approximation that the effect of steam on the average velocity of pulp negligible. The steam flow term can then be dropped from the equation. This leaves the much simpler equation:

$$\frac{dv}{dr} = \frac{rw^2}{v} - \frac{\mu r}{\mu_1} \frac{E c(r)}{w(r_2^2 - r_1^2)}$$

\hspace{1cm} (D.11)
In [59], it was found that the radial velocity gradient of the pulp \( \frac{du}{dr} \) was small in comparison to the other terms. A major simplification was then possible and equation (D.11) was rewritten as:

\[
v = \frac{r w^2}{\alpha \mu_s \frac{E c(r)}{w(r_2^2 - r_1^2)}} + \frac{du}{dr}
\]

and then, since \( \frac{dw}{dr} \ll \alpha \frac{\mu_s}{\mu_t} \frac{E c}{w(r_2^2 - r_1^2)} \)

\[
v \approx \frac{r w^2}{\alpha \mu_s \frac{E c(r)}{w(r_2^2 - r_1^2)}} \tag{D.13}
\]

or

\[
v = \frac{\mu_r}{\mu_t} \frac{r w^3 (r_2^2 - r_1^2)}{a E c(r)} \tag{D.14}
\]

A further simplification was obtained based on the assumption that the latent heat of steam was constant over the range of refining pressure. Thus from equation (D.6) and (D.8), the consistency at any radius was then given by the algebraic equation below (see next section for derivation):

\[
c(r) = \frac{c_l L (r_2^2 - r_1^2)}{L (r_2^2 - r_1^2) - c_i E (r^2 - r_1^2)} \tag{D.15}
\]

Although \( H_w \) appeared in \( m_s \), it would not affect \( c(r) \). The residence time of the pulp \( \tau \) is obtained by integrating the inverse of the local pulp velocity over the refining zone:

\[
\tau = \int_{r_1}^{r_2} \frac{dr}{v} \tag{D.16}
\]

\[
\tau = \frac{\mu_r}{\mu_t} \frac{a E c_i L}{w^3 (L(r_2^2 - r_1^2) + c_i E r_1^2)} \left[ \ln \frac{r_2}{r_1} - \frac{1}{2} \ln \left( \frac{L - c_i E}{L} \right) \right] \tag{D.17}
\]
D.3 Simplification of consistency as a function of radius

When it was assumed that the latent heat and the steam temperature were constant, $k_3 = 0$, from equation (D.6), $m_s$ became:

$$m_s = \frac{e}{L_r}$$  \hspace{1cm} (D.18)

From equation (D.8), the consistency in the refining zone became:

$$\frac{dC}{dr} = \frac{2\pi r C^2 e}{\bar{m}_d L_r}$$  \hspace{1cm} (D.19)

$$\int_{c_i}^{c} \frac{dC}{C^2} = \int_{r_1}^{r} \frac{2\pi er dr}{\bar{m}_d L_r}$$  \hspace{1cm} (D.20)

$$\left. \frac{1}{C} \right|_{c_i}^{c} = \frac{\pi e}{\bar{m}_d L_r} r^2 \bigg|_{r_1}^{r}$$  \hspace{1cm} (D.21)

$$-\frac{1}{c(r)} + \frac{1}{c_i} = \frac{\pi e}{L_r \bar{m}_d} (r^2 - r_i^2) = \frac{\pi e(r_1^2 - r_i^2)}{L_r \bar{m}_d} \cdot \frac{r^2 - r_i^2}{r_2^2 - r_i^2}$$  \hspace{1cm} (D.22)

$$-\frac{1}{c(r)} = \frac{c_i E(r^2 - r_i^2) - L_r (r_1^2 - r_i^2)}{L_r c_i (r_2^2 - r_i^2)}$$  \hspace{1cm} (D.23)

$$c(r) = \frac{c_i L_r (r_2^2 - r_i^2)}{L_r (r_2^2 - r_i^2) - c_i E(r^2 - r_i^2)}$$  \hspace{1cm} (D.24)

D.4 Remark

In conclusion, if the assumptions and simplifications are justified, equation (D.17) for the residence time is correct no matter which unit system is used for the calculation.
References


