MODELLING LATENCY REMOVAL IN MECHANICAL PULPING PROCESSES

by

Jiyang Gao

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Abstract

Latency removal is an essential step in the mechanical pulping process. It occurs in a continuous stirred-tank reactor (CSTR) and non-ideal mixing lowers the performance. In order to optimize the latency removal process and reduce the energy consumption in the operation, a kinetic study was carried out.

In this work, latency removal was studied at both the individual fibre and the pulp suspension frames of reference. In the first study, the removal of latency of individual TMP fibres was studied using optical microscopy. The fibre deflection under the influence of the heat and water absorption was measured as a function of time.

At the pulp suspension level, latency removal was characterized by the change of different pulp properties and the dependency of each property on treatment conditions was determined. Kinetic models of latency removal for secondary refiner TMP and BCTMP pulps were developed, which were based on the rate of latency elimination characterized by freeness. The kinetic study reveals that a potential energy reduction in industrial operation of latency removal can be achieved by properly increasing the power intensity to get better mixing.

These results were then complemented in a third study of a more direct measure of latency, i.e. curl index. The change in curl index of TMP pulp was examined and its dependence on temperature and other treatment conditions was determined. The development of tensile and tear strengths of TMP pulp was explored in terms of different treatment conditions and the results were analyzed in terms of fibre straightening and fibre deflocculation. Linear correlations between strength properties, curl index and freeness have been found.

In the final portion of the work an industrial case study was performed, where the latency removal of primary BCTMP pulp was examined for the purpose of optimizing an industrial latency removal process. The result of the laboratory test and the onsite measurement in the mill shows latency removal of primary BCTMP pulp is a much faster process in comparison

with the secondary BCTMP pulp, and the latency removal process in the pulp mill can be optimized using an existing smaller sized mixing chest.

Preface

A version of chapter 2 has been presented at the 97th PAPTAC Annual Conference and included in conference Technical Program Reprints and has been published in Nordic Pulp & Journal Research Journal:

Gao, J., Bennington, C.P.J., Martinez, D.M. and Olson, J.A. (2013): Latency Removal of Mechanical Pulps: Phenomenological Observations, Nord. Pulp Paper Res. J. 28(2), 198.

I designed and conducted all the experiments and analyzed the data. The written work was a collaborative effort between myself and Profs. Mark Martinez and James Olson.

A version of chapter 3 and 4 has been presented at the 98th PAPTAC Annual Conference and included in conference Technical Program Reprints:

Gao, J., Bennington, C.P.J., Martinez, D.M. and Olson, J.A. (2012): A Kinetic Model of Latency Removal in Mechanical Pulping Processes, Technical Program Reprints of Paperweek Canada 2012 – the 98th PAPTAC Annual Conference, Montreal, Canada, January 31 - February 2, 2012, PAPTAC, Montreal, Canada.

I designed and conducted all the experiments and wrote the manuscript. The data analysis was a collaborative effort between myself and Profs. Mark Martinez and James Olson.

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C_A	Local concentration of species A in a CSTR, mol/L
C_{A0}	Concentration of species A entering a CSTR reactor, mol/L
CI	Curl index, dimensionless
Cm	Consistency, %
CSF	Canadian Standard Freeness, mL
F	Canadian Standard Freeness, mL
F_A	Molar flow rate of species A, mol/s
F_{A0}	Molar flow rate of species A entering a CSTR reactor, mol/s
k	Rate constant, unit depending on the global order of reaction
k_0	Pre-exponential factor, unitless
L	Contour fibre length, mm
l	Maximum projected fibre length, mm
n	Kinetic order, unitless
r	Rate of reaction, mol/(m^3 s)
T	Disintegration temperature, °C
t	Time, s
X	Conversion of the reaction in a CSTR reactor, %
x_i	Weight proportion of the component pulp *i* in the pulp mixture, %
V	Reactor volume, m^3

Greek letters

α	Exponential function constant, unitless
β	Order to the power law function, unitless
γ	Order to the power law function, unitless
ε	Power intensity, W/kg
ν	Volumetric flow rate, m^3/s
τ	Space time, s

Subscript

$_{Cm}$	Consistency
$_{T}$	Disintegration temperature
$_{\varepsilon}$	Power intensity
$_{0}$	Initial value
$_{f}$	Final value

Glossary

Consistency (%): is the ratio of oven dry mass to the total mass of a pulp suspension.

Freeness (or Canadian Standard Freeness, CSF) (mL): measures the drainage rate of a diluted pulp suspension (3 g of pulp in 1 L of pulp suspension) as described in TAPPI Standard T 227.

Grammage (g/m^2): weight in grams of one square meter of paper or board.

Tensile Strength (N/m): measures the maximum tensile force per unit width developed in a test specimen at rupture or break. Tensile strength measures how likely a test specimen is to break when pulled at opposite ends.

Tensile Index (Nm/g): tensile strength/grammage.

Tear Strength (mN): measures the force perpendicular to the plane of the test specimen required to tear multiple plies through a specified distance after the tear has been started using an Elmendorf-type tearing tester. Tear strength measures how likely a paper will continue to tear once started.

Tear Index ($mN \cdot m^2/g$): tear strength/grammage.

Bursting Strength (kPa): measures the maximum hydrostatic pressure required to produce rupture of the test specimen using a bursting tester when a uniformly distributed and increasing pressure is applied to one of its side.

Burst Index ($kPa \cdot m^2/g$): bursting strength/ grammage.

TAPPI Standard Disintegration (using British Standard Disintegrator): consists of diluting stock to a consistency of 1.2%, followed by agitating (at a speed of 3000 rpm) the

pulp suspension at a temperature of 85-95℃ for 15 minutes, and then immediately diluting with cold water to 0.3% consistency for the measurement of the freeness and other properties.

TAPPI Standard Disintegration (using Domtar Disintegrator): consists of recirculating a pulp suspension (using a centrifugal pump) at a consistency of 2 to 2.5% and a temperature of 85 to 87℃ for 2 minutes.

Hot Disintegration: the process that the diluted pulp is subjected to high shear agitation at temperature above lignin softening temperature using any kind of disintegrator, which disperses the aggregates and straightens the fibres.

Cold Disintegration: the process that disintegration is carried out at ambient temperature using any kind of disintegrator, which disperses the aggregates but not straightens the fibres.

Fibre Flocs: Pulp fibres form networks in which each fibre is in contact with other fibres. The fibres within the networks are always distributed unevenly, giving aggregates with higher mass concentrations. These aggregates are defined as flocs.

Flocculation: the process by which fibre networks (flocs) form.

Deflocculation: the process by which fibre networks (flocs) disperse.

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I offer my sincerest gratitude to my supervisor Prof. Mark Martinez for his invaluable guidance and support throughout my Ph.D. study. I am grateful for his insightful advice, endless patience and encouragement. I offer my heartfelt thanks to my departed supervisor, Prof. Chad Bennington, for introducing me to mixing and its application in mechanical pulping and guiding me through the initial phase of my study. His empty space will be missed forever. Working in the Energy Reduction Group has been a privilege. I am grateful to Prof. James Olson for his constant support and help. Without whose knowledge and assistance this study would not have been successful. Deepest gratitude is also due to my research committee member Prof. Robert Gooding for his helpful advice and suggestion.

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Special thanks are owed to my wife Wei for her constant support throughout my years of study, for her understanding, patience and encouragement when it was most required.

Dedication

To the memory of Chad P.J. Bennington (1957 - 2010), Ph.D., P.Eng., NSERC/Paprican Chair in Chemical Pulping Technology, Professor in the Department of Chemical and Biological Engineering.

Chapter 1: Introduction

A uniform pulp quality is the basis for a uniform paper quality, and the formation of a uniform pulp suspension begins with latency removal process.

In Canada, most of the wood harvested is used to produce lumber， while the residues of lumber production and some specifically harvested logs are processed for pulp production. The pulping process is performed either chemically or mechanically. Mechanical pulping is used for products such as newsprint and some printing grades, which produces a high yield pulp of 85-95% compared to only 45% from chemical pulping. The process uses very little or no chemicals but is extremely energy intensive. The mechanical production of pulp can be divided into two broad categories: mechanical pulp production and the thermo-mechanical pulp (TMP) production, the latter in some cases with chemical support (CTMP).

In the production of TMP, wood chips are subjected to mechanical action at high temperature, moisture and pressure, and are progressively broken down to individual fibres and fibre fragments. The refining is a two-stage operation: a defibration stage followed by a fibre development stage, which separates the fibres without removing the bulk of the lignin and hemicelluloses. Being exposed to the extreme refining conditions, the fibres developed in the refining process are highly deformed and flocculated, which is, without proper treatment, not suitable for either use in papermaking process or testing.

In handling such TMP pulp, the measurement of freeness and strength related properties of these samples often gives inconsistent results with lowered pulp properties, if the samples were not disintegrated properly or when the disintegration is carried out at ambient temperature. On the other hand, samples disintegrated at elevated temperatures give consistent results with greatly improved pulp properties. In 1966, Beath *et al*. carried out research on this phenomenon and first defined the latent properties as ‘latency’ and the process which recovers the latent properties as ‘latency removal’.

Latency removal is extremely important in mechanical pulping industry. Technically, removing latency from mechanical pulp is critical to the quality of the final product as it separates and straightens the fibres, making the pulp available for the following processes as well as improving the flexibility and strength of the fibres. Paper made using latent pulp is of poor quality, e.g. low in strength properties and high in freeness. Higher paper quality is obtained after latency is removed. Commercially, removing latency from mechanical pulp saves energy. Without removing latency, only a proportion of the pulp properties developed during refining could be obtained. It was suggested (Beath *et al*., 1966) that about 5% of refining energy might represent the amount used to remove latency. The recovery of complete properties by removing latency means an increase in productive capacity or a reduction in refining energy consumption.

A study on mixing quality of industrial stock chests (Ein-Mozaffari *et al*., 2004) shows that non-ideal flows such as channeling, recirculation and stagnant regions exist in a latency chest, which lowers the performance of the chest. Under non-ideal mixing conditions, the process of latency removal relies on the compensation of other factors, e.g. more energy input for agitation, longer mixing time, etc. In this regard, the kinetic study of latency removal becomes significant. As part of a research program "Electrical energy reduction in mechanical pulping and pulp processing" aiming to reduce electrical demand for pulp production by 20%, the objective of this project is to optimize the use of energy and seek the potential of energy reduction in the recovery of the latent properties of mechanical pulp through a systematic study on latency removal and the development of a kinetic model for latency.

Chapter 2: Literature Review

Studies on latency formation and latency removal in TMP pulping processes have been carried out by a number of authors (Beath *et al*. 1966; Jones 1966; Alfthan 1976; Dawson *et al*. 1978; Mohlin 1980a; Barbe *et al*. 1984; Page *et al*. 1984; Harris and Karnis 1986; Htun *et al*. 1988; Karnis 1993). In these studies, latency formation has been found to be a process of fibre deformation and fibre flocculation resulting from the changes of fibre morphology under the extreme refining conditions. Latency removal has been described to be a process of deflocculation and fibre straightening which undoes all the changes occurred to the fibres during latency formation and restores the fibres to their original straight and isolated state.

In the beginning of this chapter, a general introduction about the change of fibre morphology in mechanical pulping process and the fundamental knowledge on the change of physical properties of the principal constituents of fibre during refining will be presented, providing background for the following critical review on latency related topics. A complete body of literature on latency formation, characterization techniques and latency removal will then be presented, followed by the literature data analysis for the development of a kinetic model of latency removal.

2.1 Changes in Fibre Morphology in Mechanical Pulping

Depending on the nature and the intensity of the mechanical treatment, fibres change in three ways (Page 1989; Seth *et al*. 1992):

- Fibre surface change – new external surfaces developed through fibrillation and new internal surfaces developed through fibre wall delamination;
- Fibre length change – increase in mean fibre length due to fibre swelling or decrease in mean fibre length due to fibre cutting and fibre break;
- Fibre morphology change – fibre deformations, i.e. curl, kinks, dislocations, crimps, microcompressions, etc., introduced or removed (Page *et al*. 1985).

When a pulp sample is subjected to intense mechanical treatment such as refining where the fibres are severely bent and compressed repeatedly, all three fibre changes occur and the pulp

becomes highly deformed and flocculated. When a pulp suspension is subjected to a gentle mechanical treatment, e.g. hot disintegrating in a British Standard Disintegrator during which the deformed fibres are repeatedly flexed, the primary changes occurred are fibre deflocculation and fibre straightening.

In either latency formation or latency removal, mechanical action is the main factor that accounts for the creation and removal of fibre flocs, while it is the change in the viscoelastic behaviors of cellulose, hemicellulose and lignin induced by heat that results in the introduction of fibre deformations and the process of fibre straightening.

2.2 Softening of Fibre Constituent Polymers

2.2.1 Structure of Cellulose, Hemicellulose and Lignin

Wood fibres consist mainly of cellulose, hemicellulose and lignin. The cell wall may be schematically viewed as crystalline, rigid cellulose microfibril bundles ordered in parallel that are surrounded by a matrix of amorphous hemicelluloses and lignin (Page 1976; Salmén and Olsson 1998), as shown in *Fig 2.1*.

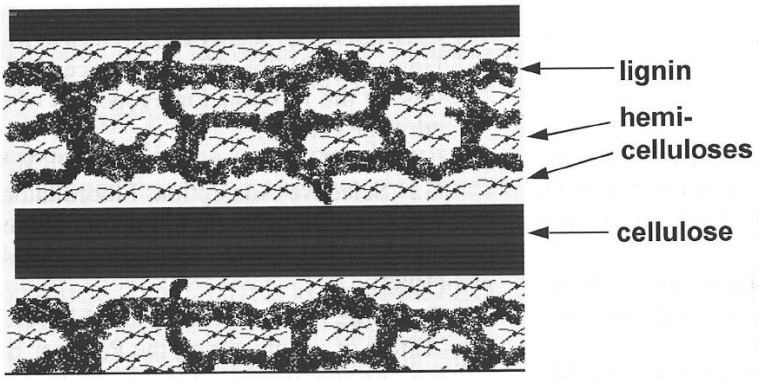

Fig 2.1 Schematic picture of the organization of the cell wall components in the secondary wall of wood fibres (Salmén and Olsson 1998).

Cellulose is the predominant structural constituent in cell walls, which provides mechanical strength and chemical stability to woods. It is a polysaccharide with a linear chain of several hundred to over ten thousand D-glucose units linked by beta-1, 4 glycosidic bonds. There are alternating crystalline and non-crystalline regions in the cellulose. Very tightly packed crystallites are formed in the crystalline region, which make it difficult for water to penetrate.

The inability of water to penetrate explains why crystalline cellulose is insoluble in water. Meanwhile, non-crystalline regions, or amorphous region in the cellulose allows water to penetrate, which breaks down the hydrogen bonding patterns and cause the swelling of the cellulosic matrix (Müller *et al*. 2000). This explains why cellulose has a poor ability to absorb water.

Hemicellulose is a polysaccharide composed of a variety of sugars including xylose, arabinose, and mannose, etc. Unlike cellulose, hemicellulose is a branched polymer that consists of shorter chains of 500 - 3,000 sugar units. Hemicellulose is the most hydrophilic polymer among the main constituents in the wood fibre. Because of its amorphous structure, the hydroxyl groups are much more accessible to water than those of cellulose.

Lignin is a complex three-dimensional polymer with phenylpropane units as the predominant building blocks, including p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol. Lignin possesses an amorphous structure which enables a large number of possible inter-linkages between individual units. Lignin fills the spaces in the cell wall between cellulose, hemicellulose and pectin components. It attaches to the hydroxyl groups of the polysaccharides cellulose and hemicellulose mainly by an ether linkage. Lignin is a much less hydrophilic material than hemicellulose and cellulose and it limits the penetration of water into the wood cells.

2.2.2 Viscoelastic Properties of Cellulose, Hemicellulose and Lignin

Amorphous materials or amorphous regions within semicrystalline materials undergo thermal softening at certain temperatures, during which the materials change from a hard and relatively brittle state into a molten or rubber-like state. The temperature at which the material undergoes thermal softening is called glass transition temperature or thermal softening temperature. Glass transition phenomena has been reported “to be associated with rotational or translational motions of polymer segments which are either directly thermally activated or made possible by the removal of existing restraining bonds” (Irvine 1984).

Lignin, hemicellulose and the amorphous regions of cellulose are amorphous polymers that display thermal softening behavior around their glass transition temperatures. Previous investigations on thermal softening of wood components showed that lignin, hemicellulose, and cellulose underwent glass transition at different temperatures (Goring 1963; Back and Salmén 1982; Irvine 1984; Page *et al*. 1984; Salmén 1984; Olsson and Salmén 1997; Salmén and Olsson 1998). When dry, all the polymers softened at high temperatures. Irvine (1984) and Salmén and Olsson (1998) reported that both dry lignin and dry hemicellulose softened at similar temperatures ranging from 130 to 190 ℃, while crystalline cellulose has been found (Goring 1963; Salmén 1984) softened at above 220 ℃. When absorbing water, the glass transition of the lignin and hemicellulose were shifted to lower temperatures as a result of the plasticizing effect of water (Goring 1963; Salmén and Back 1977; Irvine 1984). Both lignin and hemicellulose have hydroxyl and other polar groups which have the potential to be plasticized by water through the interaction between water molecules and the hydroxyl groups in lignin and hemicellulose, enabling the formation of reversible hydrogen bonds between the hydroxyl groups and individual water molecules. This water needs space between the cell wall components, which results in swelling of the fibres. When the water content increases, the softening temperatures of the polymers lower, with the temperatures determined by the concentration of accessible hydrogen bonding sites within the polymers. Under water-saturated conditions, the glass transition temperature of lignin, depending on the wood species, has been reported to be between 60 and 90 ℃ (Irvine 1984; Salmén and Olsson 1998). The transition temperature of hemicellulose approaches to the freezing point of water. In comparison, the softening temperature of cellulose was not affected.

2.3 Mechanism of Latency Formation and Latency Removal

The distinction in thermal softening behavior among lignin, hemicellulose and cellulose explains how the fibre morphology changes in refining process and how latency is formed. In the production of thermomechanical pulp, the fibres are subjected to a succession of compressive and shear stresses at high temperature of 150 - 170 ℃ and high consistency of 25 - 45%, which promotes a change in fibre shape as a result of the physical change of cellulose, hemicellulose and lignin. Consequently, the fibres become extremely deformed and entangled. When the pulp is discharged from the refiner, either being cooled in the air or

quenched in cold water, the deformations are retained. The most commonly accepted argument is given by Beath *et al*. (1966) and Jones (1966) who state that permanent deformation resulted from lignin stiffening is caused by a temperature change. When mechanical pulp is cooled, lignin in the fibres stiffens, leaving the fibres in their deformed shape. Although the elastic crystalline cellulosic microfibrils tend to resist the deformation, the elastic restoring stress in the cellulose is balanced by the stiffness of the deformed but substantially rigid hemicellulose-lignin matrix. This is undoubtedly the case for isolated fibres in the pulp, but for the majority of the fibres which are restrained in the fibre flocs, we believe that the mechanical forces, i.e. bending, friction and hooking forces (Kerekes 2006), are dominating and preventing the fibres in the fibre flocs from straightening.

From above discussion, it is clear that the mechanism to remove latency is to relax the internal stresses developed between lignin-hemicellulose matrix and cellulose. To do so, the fibres must be free from mutual entanglement. Thus latency removal is a combined process of fibre deflocculation and fibre straightening. Industrially, during latency removal, mechanical action breaks up the fibre flocs and separates the fibres. Lignin softening results in the flow of lignin and hemicellulose, which leads to the relaxation of the internal stresses developed when the fibres were cooled. Under these conditions, the now elastic cellulose, which is restrained in a bent configuration, causes the fibre to return to its straightened state before it was released from the wood (Goring 1963; Jones 1966; Beath *et al*. 1966; Alfthan 1976; Mohlin 1980a; Mohlin 1980b; Page *et al*. 1984; Htun *et al*. 1988; Mohlin and Alfredsson 1990; Karnis 1993; Seth 2006). In addition, a number of authors indicate that fibre swelling, created through the uptake of water, is an additional force that aids in the straightening process (Eriksson *et al*. 1991; Cowan 1995; Retulainen *et al*. 1998). This is speculated to be resulted from softening of the hemicellulose and the amorphous cellulose in the fibre wall (Salmén 1982), which assists fibre straightening even at room temperature.

2.4 Characterization Techniques

As a generalized term to describe the changes in different pulp properties, latency or latency removal can be characterized by any pulp property, such as freeness, curl index, dry sheet properties such as tensile strength (or tensile index), bursting strength (or burst index),

tearing strength (or tear index), or wet-web properties. Among which freeness, tensile strength and bursting strength are commonly reported (Beath *et al*. 1966; Jones 1966; Dawson *et al*. 1978; Mohlin 1980a; Htun *et al*. 1988; Karnis 1993).

A freeness test is essentially a filtration process that measures the rate of drainage of a diluted pulp suspension under standard conditions (TAPPI Standard T227). Freeness has been reported to be influenced by fibre specific surface (Forgacs 1963), fines content (Clark 1970; Mohlin 1980b; Biermann 1996) and other pulp and fibre properties (Biermann 1996). Although the introduction of freeness was based entirely on empirical deductions, an explicit theoretical expression was developed later by El-Hosseiny and Yan (1980a; 1980b) as a function of pulp consistency, pulp viscosity, specific surface, hydrodynamic specific volume and the average consistency of the pulp pad formed in a freeness tester. Among various pulp properties that are affected by latency, a 100% decrease in freeness has been reported after latency was removed (Mohlin 1980a; Karnis 1993). As the most commonly used quality control parameter in mechanical pulping and papermaking process, and a useful pulp property in characterizing strength properties of mechanical pulps (Paterson 1936; El-Hosseiny 1980b), freeness itself is a useful property for the characterization of latency removal.

Latency originates from fibre deformation. In the operation of latency removal, the fibres in the latent pulp are subjected to mechanical and thermal energies, which result in the change in fibre morphology. As a result, the most direct pulp property reflecting latency is fibre curl. Barbe *et al*. (1984) and Seth *et al*. (1992) reported a maximum of 77% decrease in curl index after latency was removed by hot disintegration.

In laboratory research, freeness experiments are carried out using a standard freeness tester and fibre curl is measured using a commercialized image-analysis based instrument such as Fiber Quality Analyzer (FQA). In mill operations, depending on the process, the freeness and fibre curl, as well as other pulp properties, are usually measured by certain automatic on-line fibre analyzing equipment such as Pulp Quality Monitor (PQM), or some semi-automatic pulp and paper testing device such as PulpExpert.

Tensile and tear strengths are two of the most important properties in studying latency. Both tensile and tear strengths are influenced by factors including fibre strength, fibre length, inter-fibre bonding strength and bonded area (Page 1969; Seth 1996; Auhorn 2006; Shmulsky and Jones 2011). However, tensile strength is closely related to inter-fibre bonding, while tear strength is influenced greatly by fibre length. Mohlin (1980a) measured the strength properties of a TMP pulp sample of Scandinavian spruce and reported a 100% increase in tensile strength and a 15% increase in tear strength after latency was completely removed. Karnis (1993) showed 65% and 55% increase in tensile strength and tear strength, respectively, after complete latency removal of a low energy (6.4 GJ/t) TMP pulp.

The properties discussed above are connected to each other. In the absence of other effects, fibre curl raises the bulk and porosity of the handsheet, which reduces the drainage resistance of pulps. As a result, the curlier the fibres are, the higher the freeness value is. In mechanical pulping process, the introduction or removal of fibre deformation has a direct effect on pulp strength properties, especially tensile and tear strengths (Beath *et al*. 1966; Jones 1966; Mohlin 1980a; Barbe *et al*. 1984; Harris and Karnis 1986; Karnis 1993). Since mechanical pulps obtain their strengths mainly from interaction between fibre surfaces and "freeness is mainly a measure of pulp specific surface area" (El-Hosseiny, Yan 1980b), freeness is also a useful pulp property in characterizing strength properties of mechanical pulps. In the literature, a linear relationship between freeness and burst strength has been reported (Paterson 1936; El-Hosseiny and Yan 1980b).

A complete list of the main pulp properties reflecting latency found in the literature has been summarized and presented in *Table 2.1*.

2.5 Latency Removal and Factors Affecting Latency Removal

As the mechanism of latency formation reveals, the way to remove latency is to undo the changes in fibre morphology through dispersing the latent pulp and straightening the fibres. In both laboratory and industrial practice, latency is removed by disintegrating the pulp suspension at low consistency and elevated temperature. In laboratory research, there are two standard methods used to remove latency - disintegrating pulp suspension at a consistency of

Table 2.1 Main pulp properties reflecting latency in the literature

Pulp Properties	**Reported by**	
Freeness, ml (or g)	Barbe *et al.* 1984 Beath *et al.* 1966 Dawson *et al.* 1978 Harris and Karnis 1986	Htun *et al.* 1988 Jones 1966 Karnis 1993
Curl index	Barbe *et al.* 1984 Karnis 1993	Page *et al.* 1984
Wet-web Properties		
Wet-web stretch, %	Barbe *et al.* 1984 Dawson *et al.* 1978	Harris and Karnis 1986 Mohlin 1980
Wet-web tensile strength, m	Barbe *et al.* 1984	Mohlin 1980
Wet-web breaking length, km	Barbe *et al.* 1984 Dawson *et al.* 1978	Harris and Karnis 1986
Dry Handsheet Properties		
Burst index, kPa m^2/g	Barbe *et al.* 1984 Beath *et al.* 1966 Dawson *et al.* 1978	Jones 1966 Harris and Karnis 1986 Karnis 1993
Stretch, %	Barbe *et al.* 1984 Dawson *et al.* 1978 Harris and Karnis 1986	Jones 1966 Karnis 1993 Mohlin 1980
Tensile strength, kN/m	Barbe *et al.* 1984 Karnis 1993	Mohlin 1980
Zero-span breaking length, km	Barbe *et al.* 1984 Dawson *et al.* 1978	Karnis 1993
Breaking length, km	Barbe *et al.* 1984 Harris and Karnis 1986	Jones 1966
Modulus of elasticity, km	Karnis 1993	Mohlin 1980
Tear index, $mN.m^2/g$	Beath *et al.* 1966 Dawson *et al.* 1978 Harris and Karnis 1986	Jones 1966 Karnis 1993 Mohlin 1980

1.2% and a temperature of 85 ℃ in a British Standard Disintegrator for 15 minutes (TAPPI Standard T 205); and recirculating a 2% consistency pulp suspension at a temperature of 85 ℃ for 2 minutes using Domtar Disintegrator (TAPPI Standard T 262). In industrial operation, latency is removed by passing the pulp through a latency chest, where high consistency (45-50%) pulp is diluted to 3-5% and is agitated at elevated temperature of 80-90 ℃ for 20-60 minutes. In addition to typical latency removal at low consistency, method of removing latency from medium consistency pulps by pumping has also been patented

(Prough *et al*. 1986). By pumping the pulps utilizing a centrifugal pump at a consistency of 8-25%, the fluidization imparting sufficient energy to the pulp to remove the latency.

Removing latency of mechanical pulps is dependent on the treatment conditions, i.e. disintegration temperature and energy of the mechanical action, and is affected by factors such as pulp consistency (Beath *et al*. 1966; Jones 1966; Alfthan 1976; Dawson *et al*. 1978; Htun *et al*. 1988; Karnis 1993).

Disintegration temperature has been reported as a major factor in latency removal (Beath *et al*. 1966; Jones 1966; Dawson *et al*. 1978), which, as previously discussed, has been found to result from the change of viscoelastic properties, especially thermal softening behavior of lignin, hemicellulose and cellulose. In latency removal operation, the latent pulp is disintegrated at a temperature above the lignin softening temperature. As a result, the pulp is deflocculated and the stiffened lignin in the fibres is softened. The restoring stress of the elastic cellulose then returns the deformed fibres to their original straightness.

The effect of disintegration temperature on latency removal was evaluated by examining the change in freeness of the pulp suspension disintegrated at different temperatures (Beath *et al*. 1966; Alfthan 1976; Htun *et al.* 1988). The research results show that latency was increasingly released as disintegration temperature increased from ambient temperature up to 95℃ (*Figs 2.2 - 2.4*). It has been noted (Alfthan 1976; Htun *et al*. 1988) that there was a slight acceleration in freeness releasing rate around the lignin softening temperature (*Figs 2.3* and *2.4*). The finding corresponds well to the thermal softening behavior of lignin that when the temperature is approaching to lignin softening temperature, the lignin becomes more softened and the fibres become more flexible, which facilitates fibre deflocculation and fibre straightening process and slightly speeds up the rate of latency releasing.

In all the studies, the experiments were carried out at different temperatures using British Standard Disintegrator or other mixing devices. However, no information on temperature control has been reported by any of the researchers. In disintegrating hot pulp suspensions without insulation or heat supply, the inevitable temperature drop resulted from heat loss will

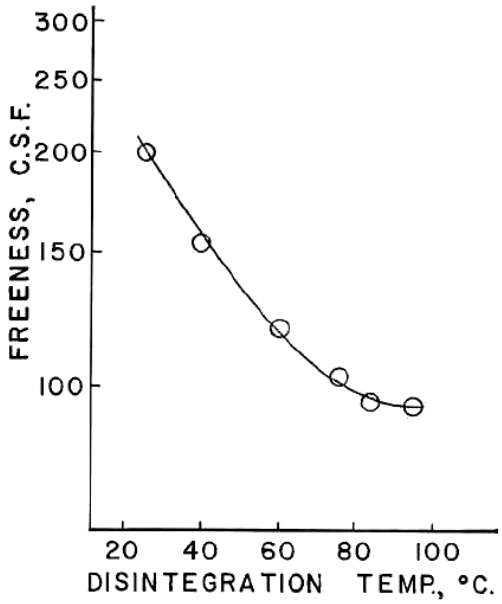

Fig 2.2 The effect of disintegration temperature on latency removal. Measurements were made by diluting a high-consistency refiner pulp to 1.25% and disintegrating in a British Standard Disintegrator for 20 minutes. Figure is modified from Beath *et al.* (1966).

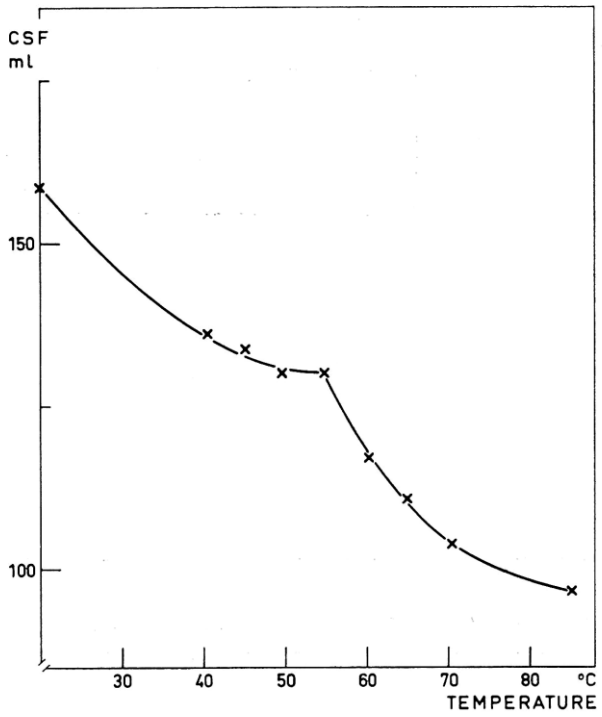

Fig 2.3 Disintegration of TMP pulp at different temperatures (Alfthan 1976).

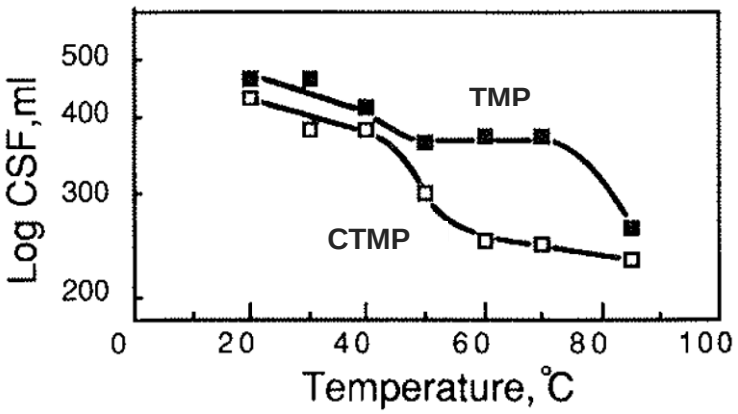

Fig 2.4 Latency removal in TMP pulp at different disintegration temperatures. The experiments were carried out followed SCAN Standard C.18/M2 (Htun *et al.* 1988).

slow down the process of latency removal, making the experimental data invalid to be analyzed for the development of a kinetic model of latency removal. In this study, temperature control system has been designed to eliminate the effect of temperature change in the experiment.

Mechanical action plays an important role in removing latency. Beath *et al*. (1966) examined the effect of mechanical action on latency removal through sampling at different times. Dawson *et al*. (1978) evaluated the effect of mechanical action using a prototype Domtar Disintegrator. The results show that latency removal is function of mechanical energy, involving both factors of power intensity and time. To remove the same amount of latency, the application of higher power intensity will reduce the time required to complete the treatment. Beath *et al*. (1966) proposed that effectiveness of mechanical action on latency removal was "ascribed to the breaking up of flocs rather than to any direct effect of mechanical action on the fibres".

Using a Valley beater, Beath *et al*. (1966) carried out two tests at 26 and 55 ℃, respectively. The results show that latency is continuously released for both runs at 26 and 55 ℃, and the rate of latency removal is faster for beating at 55 ℃. In addition, experiments of "beaten only" and "beaten then hot disintegrated" were compared, showing that mechanical action alone can remove latency completely. Clearly, this conclusion does not fit with the

hypothesis that latency removal is thermally-controlled. This is because the nature of the treatment is no longer a process of latency removal only. The application of Valley Iron Laboratory beater provides strong mechanical treatment to the fibres, which results in the extreme changes in fibre morphology as discussed in the beginning of this chapter. A combined effect of refining and latency removal resulted from the intensive treatment makes the experimental results difficult to explain.

By varying the power intensity applied in the experiment through treating the pulp sample at different the recirculation rates in a prototype Domtar disintegrator, Dawson *et al*. (1978) found that higher energy intensity significantly accelerated the rate of latency removal (*Fig 2.5*) At low recirculation rate, i.e., at 1 min^{-1}, about 15 minutes was required, the same as for the result obtained using a British Standard Disintegrator. As the recirculation rate increased, the time required to remove all the latency decreased significantly.

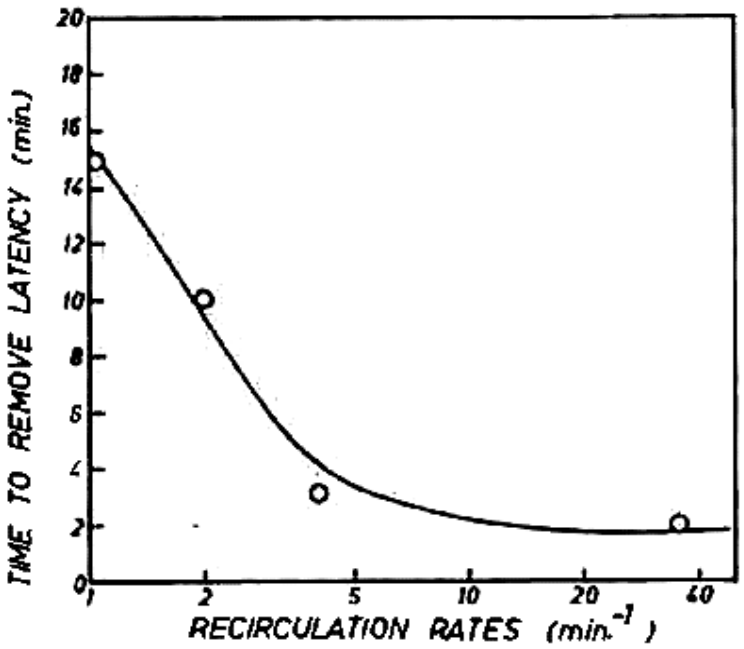

Fig 2.5 The time required to remove latency against the logarithm of the recirculation rate (Dawson *et al*. 1978).

Latency removal is affected by pulp consistency. Beath *et al*. (1966) reported that over the range from 0.75 to 2%, consistency had no effect on latency removal. While for higher consistency up to 15.6%, the higher the pulp holding consistency was the higher the fibre

restraint was, and the less the latency was removed. Dawson *et al*. (1978) examined the hot disintegration of refiner pulp at a temperature of 85 ℃ but with consistencies from 1 to 3% using both a prototype Domtar Disintegrator and a British Standard Disintegrator. They concluded that consistency within this range had no effect on final freeness after latency was removed. Yet it has been noted that both reported results neglected an important factor in the experiment - power intensity. The examination of power consumption for the disintegration of TMP pulp carried out in this study at consistencies from 1.2 to 3.0% using a British Standard Disintegrator showed that power increased dramatically as the consistency increased. From 1.2 to 3.0%, the power in the disintegration of a 2 L pulp suspension increased from 31 to 112 W. In addition, the effect of consistency on latency removal, which will be discussed in following chapters, is through changing the rate of latency releasing, rather than changing the final value after latency is completely removed. In consideration of these findings, the experimental data should be analyzed on the basis of constant power or energy input, and the consistency-effect-related data reported by Beath *et al*. (1966) and Dawson *et al*. (1978) are suggested not to be used directly without prior analysis.

2.6 Literature Data Analysis for Model Development

There is no kinetic model that has been reported in the literature. Since the studies on latency removal in the literature were carried out on different types of pulps and at various treatment conditions, the attempt to develop and complete a kinetic model using the literature data is not able to be achieved. As a result, a systematic study on latency removal will have to be designed and carried out for the model development. In this section, however, a preliminary kinetic model has been proposed to determine the kinetic order of latency removal based on the data available in the literature.

Experimental result (Beath *et al*. 1966) shows that when the pulp is disintegrated, its freeness decreases continuously along with the disintegration time until a constant value is reached (*Fig 2.6*). Different from ordinary chemical reaction where one or more reactants change in concentration, latency removal can be considered as a hypothetical reaction in which the "reactant", the pulp fibre, changes their morphology. The process is characterized by a decrease in freeness, with the rate of decrease expressed by a kinetic model.

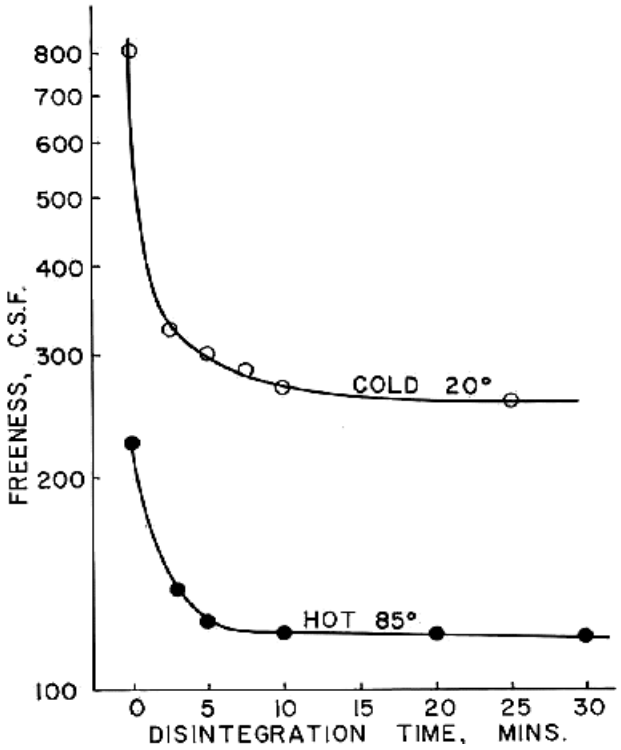

Fig 2.6 Latency release in standard cold and hot disintegrations. Measurements were made by disintegrating high consistency refiner pulp at 1.25% consistency and at 20 and 85 ℃, respectively, in a British Standard Disintegrator for various time intervals (Beath *et al*. 1966).

A simple model is proposed herein to model latency removal, expressed by the net change of the freeness:

$$-\frac{dF}{dt} = k \cdot \left(\frac{F - F_f}{F_0 - F_f} \right)^n \qquad \textbf{(2.1)}$$

where n is the kinetic order; k is the rate constant; and F_0 and F_f are the initial and final freeness values, respectively.

In the literature, the value of F_f was measured after the pulp was disintegrated at a temperature of 85 ℃ for a length of time until there was no more change in the value of freeness and the curve leveled off. The only reported value of F_0 (Dawson *et al*. 1978) was measured on the pulp suspension that has been disintegrated at a temperature of 27 ℃ for 15 minutes. This is believed to be inaccurate as these researchers ignored the effect of fibre deflocculation by dispersing the pulp suspension and breaking up the fibre flocs before

measuring the value of freeness.

An explanation of the above statement is that latency is the difference between the state of pulp sample after being completely disintegrated, where the pulp is dispersed and the fibres are straightened, and the initial state of the pulp sample, where the sample has not been treated or incompletely treated. As a result, either fibre deflocculation or fibre straightening will result in latency removal. Actually, the extent of fibre deflocculation has great influence on latency removal, which will be discussed in Chapter 5.

As latency removal is influenced by the disintegration temperature, energy applied and pulp consistency, the rate constant is dependent on the disintegration temperature *T*, the power intensity ε, and the pulp consistency *Cm*, i.e.

$$k = function\ (T, \varepsilon, Cm) \qquad \textbf{(2.2)}$$

As there is no form given in the literature, it is necessary to quantify the kinetic order in *Eq 2.1* and the functional form of *Eq 2.2*. The data available in the literature is analyzed for the determination of the kinetic order and presented below.

2.6.1 Kinetic Order

There are two methods (Fogler 2006), i.e. integral and differential methods, available to determine the kinetic order of the proposed model of latency removal for a given set of disintegration conditions (energy input, temperature and consistency). In this section, both the differential and the integral analysis are explored.

2.6.1.1 Differential Analysis

Taking the natural logarithm of *Eq 2.1* gives

$$\ln\left(-\frac{dF}{dt}\right) = n\ln\left(\frac{F-F_f}{F_0-F_f}\right) + \ln k \qquad \textbf{(2.3)}$$

The plot of $\ln\left(-\frac{dF}{dt}\right)$ versus $\ln\left(\frac{F-F_f}{F_0-F_f}\right)$ will give a linear line, and *n* and *k* can be obtained from the slope and intercept of the line.

Three sets of experimental data available in the literature, i.e. hot disintegration using Domtar Disintegrator by Dawson *et al*. (1978); hot disintegration using British Standard Disintegrator by Dawson *et al*. (1978) and hot disintegration using British Standard Disintegrator by Beath *et al*. (1966) are examined. The results are presented in *Figs 2.7 - 2.9*, showing that the latency removal is a 1st order process.

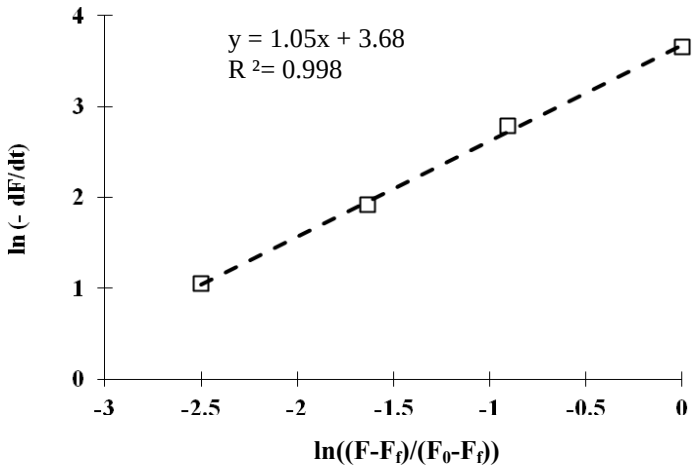

Fig 2.7 Data analysis of latency removal by disintegration method at 85℃ (Dawson *et al*. 1978) shows that latency removal is a 1st order process. Source data are listed in Table A.1 in Appendix A.

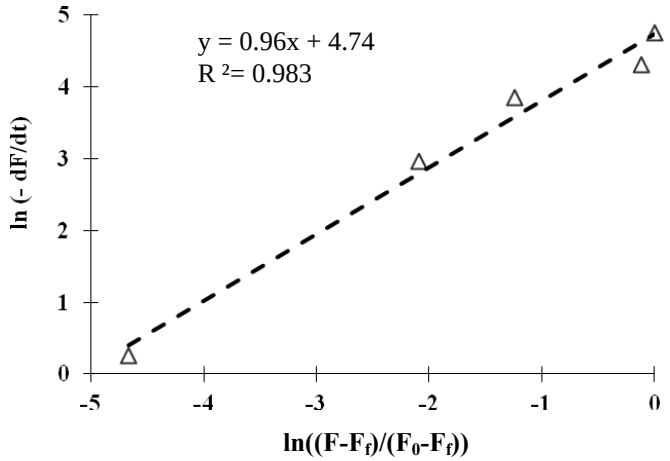

Fig 2.8 Data analysis of latency removal by recirculation method (Dawson *et al*. 1978) shows that the latency removal is a 1st order process. Source data are listed in Table A.1 in Appendix A.

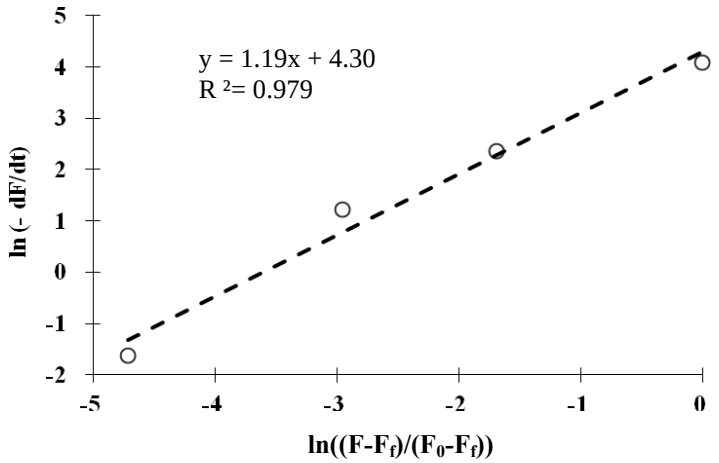

Fig 2.9 Data analysis of latency removal in a British Standard Disintegrator at 85 ℃ (Beath *et al*. 1966) shows that the kinetic order of latency removal is 1.2. Source data are listed in Table A.1 in Appendix A.

2.6.1.2 Integral Analysis

The integration of *Eq 2.1* gives

$$\begin{cases} \ln\left(\frac{F-F_f}{F_0-F_f}\right)_t - \ln\left(\frac{F-F_f}{F_0-F_f}\right)_0 = -\frac{k}{F_0-F_f}\cdot t & \text{(when } n=1\text{)} \quad \textbf{(2.4a)} \\ \left(\frac{F-F_f}{F_0-F_f}\right)_t^{-n+1} - \left(\frac{F-F_f}{F_0-F_f}\right)_0^{-n+1} = -\frac{(1-n)\cdot k}{F_0-F_f}\cdot t & \text{(when } n\neq 1\text{)} \quad \textbf{(2.4b)} \end{cases}$$

When linear relationship between $\begin{cases} \ln\left(\frac{F-F_f}{F_0-F_f}\right)_t & \text{and } t \quad \text{(when } n=1\text{)} \\ \left(\frac{F-F_f}{F_0-F_f}\right)_t^{-n+1} & \text{and } t \quad \text{(when } n\neq 1\text{)} \end{cases}$

is obtained, the kinetic order n can be determined.

For all three sets of experimental data shown in the differential analysis, different values are assigned to the kinetic order n and the linear trendline equations and corresponding R^2 are obtained. Practically, the best linear relationship can be determined by comparing the R^2 values of the linear trendline equation. The plots of R^2 versus n are shown in *Figs 2.10 - 2.12*.

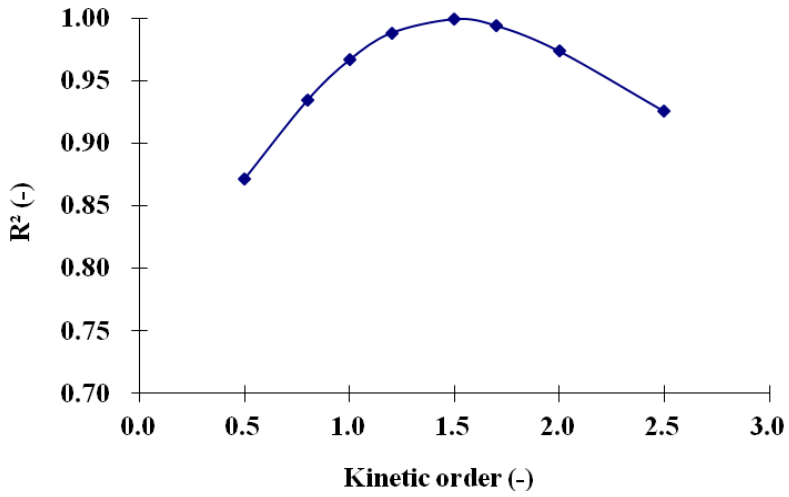

Fig 2.10 The plot of R^2 against n using the data of hot disintegration (Dawson *et al*. 1978) shows that the kinetic order of latency removal is 1.5. Source data are listed in Table A.2 in Appendix A.

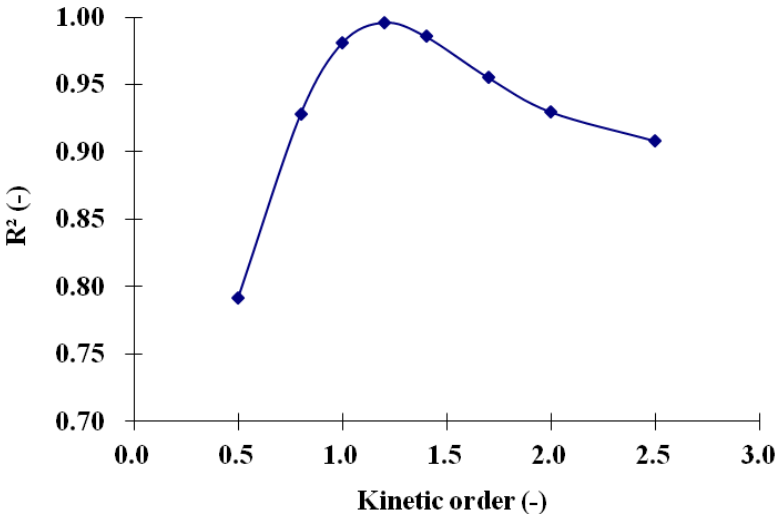

Fig 2.11 The plot of R^2 against n using the data of latency removal by recirculation method (Dawson *et al*. 1978) shows that the kinetic order of latency removal is 1.2. Source data are listed in Table A.2 in Appendix A.

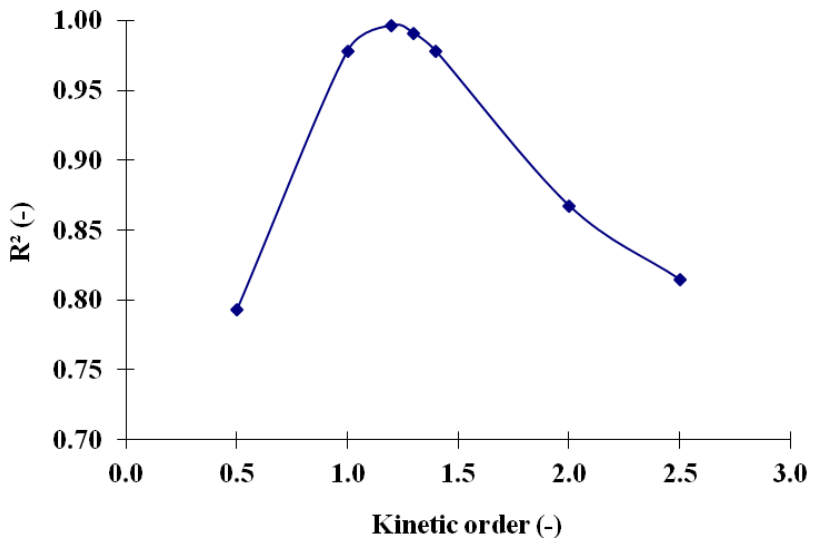

Fig 2.12 The plot of R^2 against n using the data of hot disintegration (Beath *et al*. 1966) shows that the kinetic order of latency removal is 1.2. Source data are listed in Table A.2 in Appendix A.

The kinetic orders determined by the integral method are 1.5, 1.2 and 1.2, respectively, which are higher than those determined by the differential method. However, what drew our attention were the initial values of freeness reported by the researchers. We noticed there is big difference between the reported values and the freeness of the untreated pulp sample, the initial value of freeness for any given pulp sample. For example, the initial freeness reported in *Fig 2.7* is 400 mL, the value measured after the pulp sample was cold disintegrated at 27 ℃ for 15 minutes. Apparently, cold disintegration results in fibre deflocculation and removes certain amount of latency. Similarly in *Fig 2.9*, also seen in *Fig 2.6*, the lower value of 223 mL reported by Beath *et al.* (1966) is believed to be the freeness of the pulp sample after it was treated, even though the details of the treatment was not covered in their paper. In order to determine the kinetics of latency removal, the correct initial freeness should be value of the original untreated pulp sample, e.g. 809 mL. The application of the value of 809 mL in all three cases determines that the kinetic orders are 1.7, 1.7 and 1.8 by differential method and 1.7, 1.4 and 1.3 by integral method.

The kinetic orders obtained through the analysis of the literature data varies from one researcher's result to another. Meanwhile, the data available in the literature are not sufficient for the determination of the overall kinetic expression. This points to the overall need of this

study, where a series of new experiments need to be designed and carried out, during which the changes of key parameters, i.e. disintegration temperature, power intensity and consistency, as a function of time are monitored, and the overall kinetic expression and the unknowns in the expression will be determined.

The success in latency removal depends not only on the understanding of the influence of each factor in latency removal, but also on the determination of the relationship among these factors so that the optimal operation condition is able to be specified. In reality, latency chests in mechanical pulp mills are often designed empirically and graphically. Typically, an industrial latency chest is rectangular in shape, 10-12 meters long, 6-7 meters wide and 3-6 meters high (Ein-Mozaffari *et al*. 2004), with a stock operating height of 60-85% of the height of the chest. The locations of the mixer, stock inlet and outlet vary from one mill to another. Depending on the design of the chest and the operation conditions, the residence time in latency chest varies from 20 to 60 minutes. Rather than achieving complete motion, latency chest is operated in a zone-agitation mode. As a result, good mixing in the agitation zone and poor mixing outside the mixing zone exist simultaneously. The existence of non-ideal mixing (recirculation, bypassing, dead zone, etc) lowers the performance of the chest. It is then essential to determine the kinetics of latency removal for the purpose of potential optimization of latency removal as well as energy reduction in mechanical pulping processes.

2.7 Research Objectives

As part of the project -"Electrical Energy Reduction in Mechanical Pulping and Pulp Processing" which aims at reducing electrical energy consumption in mechanical pulping by 20% through scientific discovery and the development of new technology while maintaining or improving product quality and production, this project is to develop a kinetic model of latency removal and apply it for optimizing the use of energy in the recovery of the latent properties of mechanical pulp. This intensive and systematic study is not only to determine the change of fibre and pulp properties in latency removal and the mechanisms responsible for these changes, but also to understand better what happens to the fibres during latency removal as well as to find solutions to energy reduction in latency removal.

As a result, the specific objectives of this research are as follows:

1. Phenomenological observations of latency removal

- To understand better the mechanism of fibre straightening in latency removal and to elucidate the rate by which individual mechanical pulp fibres straighten during latency removal (addressed in Chapter 3);

2. Modeling latency removal in mechanical pulping processes by freeness

- To evaluate the dependence of latency removal on the treatment conditions, i.e. temperature, power intensity and consistency, and to develop a kinetic model (in terms of freeness) to model latency removal as a function of the key variables (addressed in Chapter 4);
- To optimize latency removal process and seek the potential of lowering energy consumption in latency removal process (addressed in Chapter 4 and Chapter 7);

3. Characterizing latency removal in mechanical pulping processes by fibre curl and strength properties

- To interpret the change of these pulp properties in latency removal and establish the relationship among these properties and to help to characterize the fibre deflocculation process in latency removal (addressed in Chapter 6);

4. Latency removal of primary BCTMP pulp

- To evaluate feasibility of latency removal of primary BCTMP pulp in a process renovation involving changes in operational parameters (addressed in Chapter 7).

2.8 Thesis Outline

Chapter 3 is focused on phenomenological observations of latency removal at individual fibre level. Through observing fibre straightening at various conditions, the chapter presents the results on the change in fibre morphology and the determination of the rate of fibre straightening.

Chapter 4 presents the results on modeling latency removal in terms of freeness for a secondary refiner TMP and a secondary refiner CTMP pulps. The model expression has been determined as a function of disintegration temperature, power intensity and consistency, and the development and application of the model reveals there is potential of energy reduction in mechanical pulping processes.

Chapter 5 presents the preliminary study on the application of the kinetic model in characterizing industrial latency removal process. A mixing rule was explored and verified to predict the freeness of the pulp mixture of perfectly mixed and non-perfectly mixed streams.

Chapter 6 presents the results on the characterization of latency removal by fibre curl and strength properties. The relationships between property pairs have been explored and the influence of the existence of fibre flocs on the measurements of curl index and strength properties has been discussed.

Chapter 7 presents the results on latency removal of primary BCTMP pulp, an extended study toward latency removal in low consistency refining process. In addition, the chapter also explores the application of the kinetic model of latency removal in modeling the operation of latency removal in industrial environment.

The summary of the most significant points made in the main preceding chapters, the contribution to knowledge and recommendations for future research are presented in Chapter 8.

Chapter 3: Phenomenological Observation of Latency Removal

Fibres are straight in the wood, but become extremely deformed and flocculated in the mechanical pulping process. Different deformations, i.e. curl, kink, twist, crimp, etc., have been observed and studied by many researchers The review of these studies can be found in the paper of Page *et al*. (1985). In the literature, fibre straightening was reported in the study of latency removal at either a macroscopic level by hot disintegration of pulp suspension (Beath *et al*. 1966; Jones 1966; Alfthan 1976; Dawson *et al*. 1978; Mohlin 1980a; Harris and Karnis 1986; Htun *et al*. 1988; Karnis 1993), or, at phenomenological level through heat treatment on isolated fibres (Jones 1966; Alfthan 1976; Karnis 1993).

At the individual fibre level, Jones (1966) evaluated the effect of heat treatment on individual curled and kinked fibres and a kinked fibre bundle of a mechanical pulp through comparing microscopic photos of the tested fibres before and after they were heated. In the experiment, the selected fibre was suspended in a pool of water on a slide. After photographed, the slide was placed on a hot plate to heat the water to approximate 100℃, and then returned to the microscope for photographing. Jones found that the extremely deformed fibres and fibre bundle were almost completely straightened after the heat treatment. A similar experiment with a number of twisted fibres was carried out by Alfthan (1976), who put the selected thermomechanical pulp fibre into a water pool created by a cover glass glued to a specimen glass. Space was left for the fibre to move in the water. The specimen glass was then placed in 90℃ water for five minutes. Photos taken before and after the treatment showed that in each experiment the twisted fibre was straightened out after it was heated.

Although the microscopic study on fibre straightening has received considerable attention in the literature, one of the open remaining questions in this area relates to the time required for the straightening process to occur. In this work we attempt to complement this body of knowledge by: (a) elucidating the rate by which individual mechanical pulp fibres straighten in removing latency of isolated TMP pulp fibres and (b) understanding better the kinetics of the fibre straightening process in the operation of latency removal. To do so we visualize the motion of individual isolated fibres undergoing heat treatment. We do so to gain insight into the relative importance of water uptake and temperature on the straightening event.

3.1 Materials Methods

Never-dried western hemlock (Tsuga heterophylla) pulp fibres obtained after secondary high consistency (45%) refining from Howe Sound Pulp & Paper Ltd (HSPP) were used in the study. The pulp was stored in a cold room at a temperature of 6°C. In order to determine the fibre length, hot disintegration was carried out where a 3% consistency pulp sample was disintegrated using a customized mixer at a temperature of 85°C and all latency was removed. Fibre length of the pulp samples were then measured using an OpTest Fibre Quality Analyzer (FQA). The values of mean lengths obtained were 0.862 mm (arithmetic), 1.947 mm (length weighted) and 2.376 mm (weight weighted), respectively.

Before the beginning of the experiment, typical curled and kinked fibres were selected from isolated fibres in the pulp and were conditioned by allowing them to reach room temperature.

An experimental system consisting of a Nikon SMZ-1 optical microscope, a USB microscope video camera and a laptop were set up for observation and recording of the changes of fibre structure. In each experiment, the specimen was prepared where a sample fibre placed on a glass slide was held in place by a cover glass pinning one end of the fibre. The other end of the fibre was free to deform under the action of the applied heat and moisture. In each test one or several drops of distilled water were introduced using a syringe to fully immerse the fibre.

The experimental protocol consisted of immersing the fibre in water held at a fixed temperature. Two experimental conditions are reported in this work. In the first series of experiments, the fibres are saturated with 23 ℃ water and then heated with 85 ℃ water. In the second series of experiments, saturated fibres are subjected sequentially to temperatures of 23 ℃, 50 ℃, and then 85 ℃. After each treatment with water, the fibre was air-dried before proceeding to next treatment.

In each experiment, the deflection of the fibre was recorded digitally at a framing rate of 30 images per second. The frames in the videos were extracted using video-to-image converting software for analysis. In the photos, the projected and contour lengths of each fibre were

measured digitally and curl indices were manually calculated. In this study, the deflection of the fibre is presented as curl index *CI*, which is related to the ratio of the length between the contour fibre length *L* to its maximum projected fibre length *l*, i.e.

$$CI = \frac{L}{l} - 1 \qquad \textbf{(3.1)}$$

3.2 Results

A large number of trials were conducted and results for each series of experiments are presented below. For the first series, the images of the change of fibre morphology of a representative curled and a kinked fibre are presented in *Figs 3.1* and *3.2*.

Being treated with room-temperature (23 ℃) water, as shown in *Fig 3.1 (a) – (c)* and *Fig 3.2 (a) –(c)*, we observed phenomenologically water uptake and a subsequent deflection of the fibres. However, when the fibres were then dried at room conditions, they sprang back toward their original deformed shapes. This limited extent of fibre "straightening" when absorbing water is believed resulted from a combined effect of hemicellulose softening and fibre swelling (Eriksson *et al*. 1991; Cowan 1995; Retulainen *et al*. 1998). As discussed in previous chapter, the hemicellulose is hydrophilic, which acts as swelling agent that contributes most of the swelling of the fibre. Back and Salmén (1982) reported that amorphous celluloses and hemicelluloses softened below room temperature in a water-saturated state. In the experiment, the hemicellulose in the fibre softens and flows in the fibre wall when room-temperature water was introduced to the fibre, which changed the force balance established between the rigid lignin-hemicellulose matrix and the elastic cellulose, resulting in the fibre deflection. Meanwhile, the fibre wall swells and increases in volume when absorbing water, making contribution to the fibre deflection. But this contribution is only temporary and disappears when the fibre is dried, which explains that when the water evaporated, the fibre was bouncing back toward its initial state of deformation.

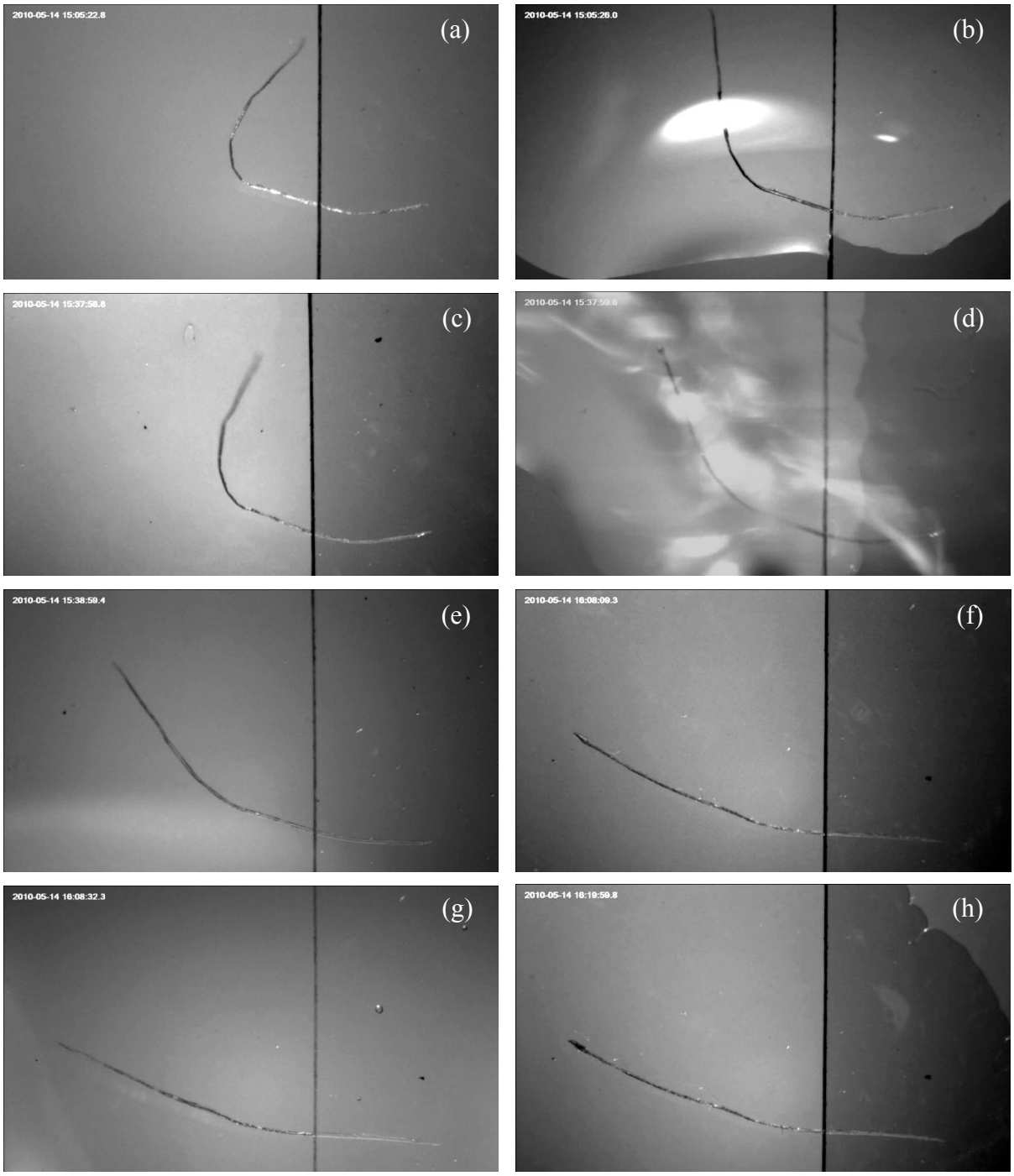

Fig 3.1 Straightening of a representative curled fibre by hemicellulose softening and lignin softening. (a) Original curled fibre; (b) About one second after being treated by a couple of drops of 23 ℃ water; (c) 23 ℃ water evaporated completely; (d) 0.3 seconds after being treated by a few drops of 85 ℃ water; (e) One minute after treated by 85 ℃ water; (f) 85 ℃ water evaporated completely; (g) Treated by 23 ℃ water again; (h) 23 ℃ water evaporated completely.

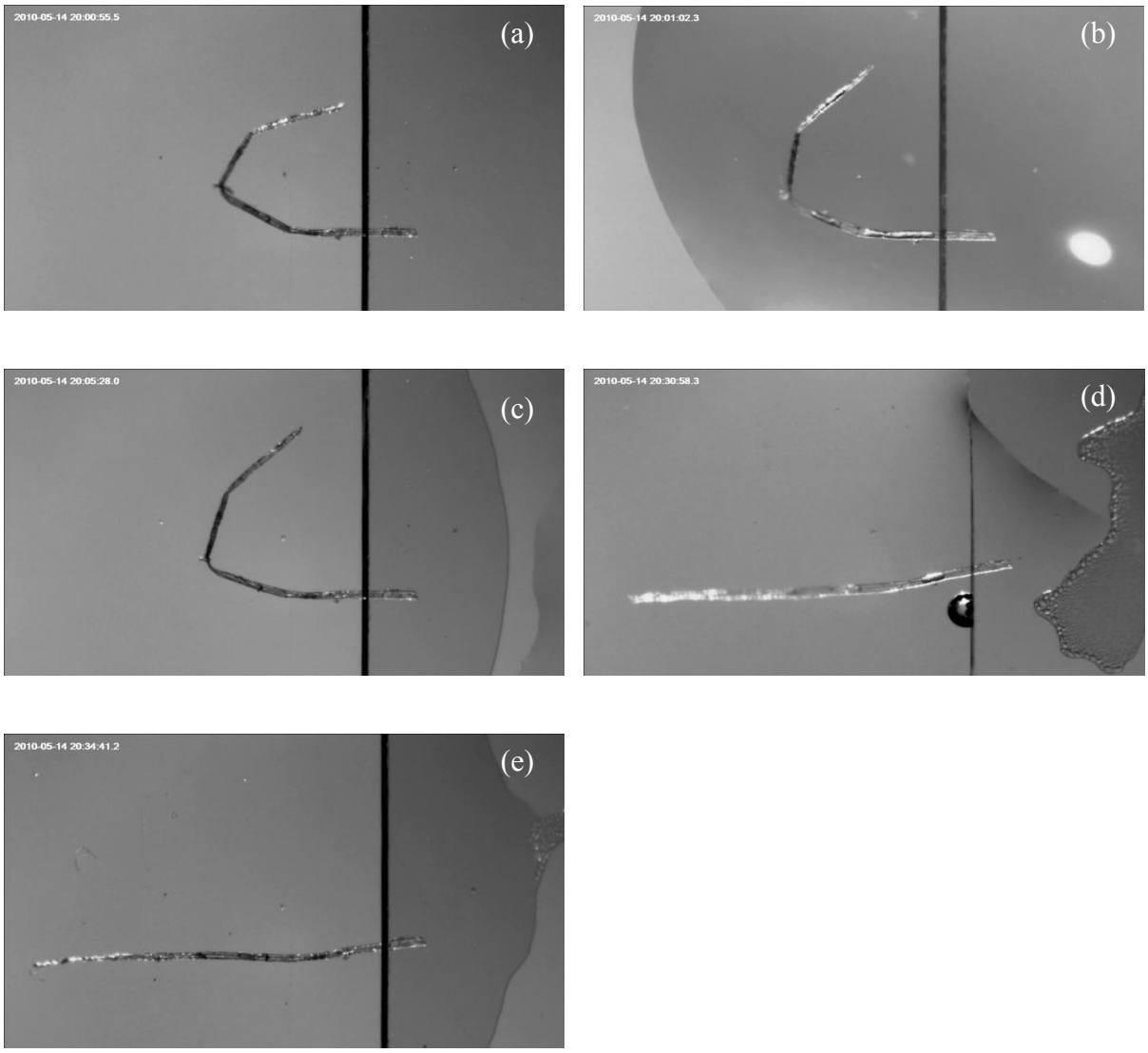

Fig 3.2 Straightening of a kinked fibre by hemicellulose softening and lignin softening. (a) Original kinked fibre; (b) Treated by a couple of drops of 23 ℃ water; (c) 23 ℃ water evaporated completely; (d) Treated by a few drops of 85 ℃ water; (e) 85 ℃ water evaporated completely.

Fig 3.1 (d) – (f) and *Fig 3.2 (d) – (e)* illustrate the effect of heat on fibre straightening, which results from lignin softening. Subjected to a few drops of water at 85 ℃, the fibres completed their straightening to a great extent within a few tenths of a second, followed by a further relaxation until reaching their maximum straightening. In comparison with the limited "straightening" at room temperature, heat treatment permanently straightened the fibres. This is verified in the following water uptake test for the curled fibre (*Fig 3.1 (g) – (h)*). Here we

see that no bounce back to its initial curl was observed after it was treated with the 23℃ water again.

The qualitative result was followed by quantitative analysis. The changes in deflection of the curled fibre, characterized by curl index, were plotted as a function of time for two different heat and moisture conditions (*Fig 3.3)*. *Fig 3.3(i)* shows the change in curl index of the fibre when it was subjected to room-temperature water. In the case presented in this figure, fibre straightening occurred over a period of approximately 1-2 seconds. In *Fig 3.3(ii)*, the water was allowed to evaporate over a period of time of about 10 minutes and we observed some recovery of the original curliness in the fibre. Once dry, the fibre was re-immersed in 85℃ water, see *Fig 3.3(iii)*, and here the fibre straightened to its maximum extent. The straightening occurred over a time of approximately 1 second. The interesting feature of this graph is that in region *(iv)*, where the water has evaporated from the fibre, the fibre did not return to its original curl position. In this case the fibre straightening is permanent. In order to present the general trend of the change in fibre straightening, seven more observations have been made. We find a similar qualitative finding when we repeated the experiment and the arithmetic average value of curl index for all fibres tested are presented in *Fig 3.4*. Since each fibre is different in terms of the type and extent of deformation, the curl indices reported in this figure and *Fig 3.6* in the paper are normalized values calculated as the difference between the initial value of the curl index and the minimal curl index divided by the minimal curl index for each series of test on a sample fibre.

A similar finding is shown in *Figs 3.5* and 3.*6* where we present the experimental results illustrating the extent of fibre straightening as a function of temperature on a representative fibre (*Fig 3.5*) and an average of six sample fibres (*Fig 3.6*). Again we see similar results for all the fibre tested that fibre straightening occurs through the action of water uptake and heat, and the permanence of this effect is achieved at a temperature higher than lignin glass transition point.

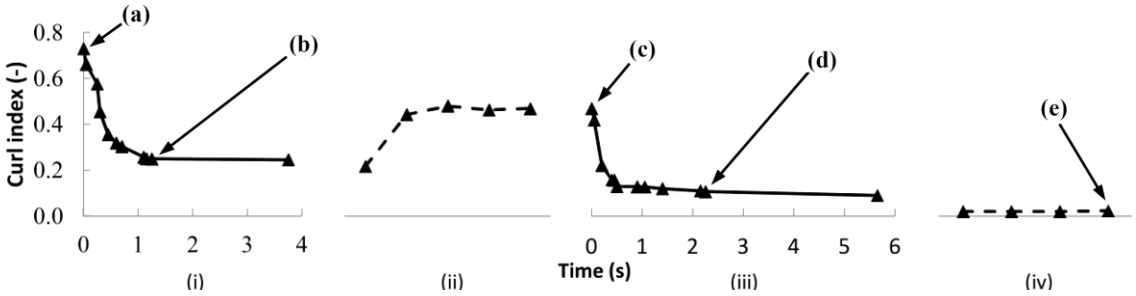

Fig 3.3 Representative result illustrating the change in curl index as a function of time and type of temperature and moisture treatment. (i) Moistening of a fibre originally in a 45% consistency suspension with a drop of water at 23°C. (ii) The change in curl index as the drop of water evaporates at room temperature. (iii) Re-immersion of the fibre in water but in this case the water is at 85°C. (iv) Evaporation of the water and the subsequent drying of the fibre. Real fibre images for selected points (a) - (e) can be found in *Fig 3.1*.

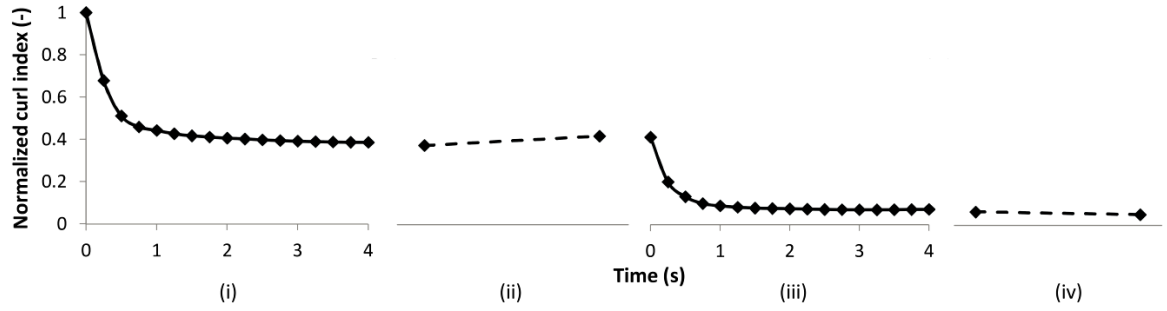

Fig 3.4 Illustration of the change in curl index as a function of time and type of temperature and moisture treatment. Each data point shown in this figure represents an arithmetic average of curl index of eight sample fibres. (i) Moistening of a fibre originally in a 45% consistency suspension with one or more drops of water at 23°C. (ii) The change in curl index as the drop of water evaporates at room temperature over a period of time of 10-20 minutes. (iii) Re-immersion of the fibre in water but in this case the water is at 85°C. (iv) Evaporation of the water and the subsequent drying of the fibre.

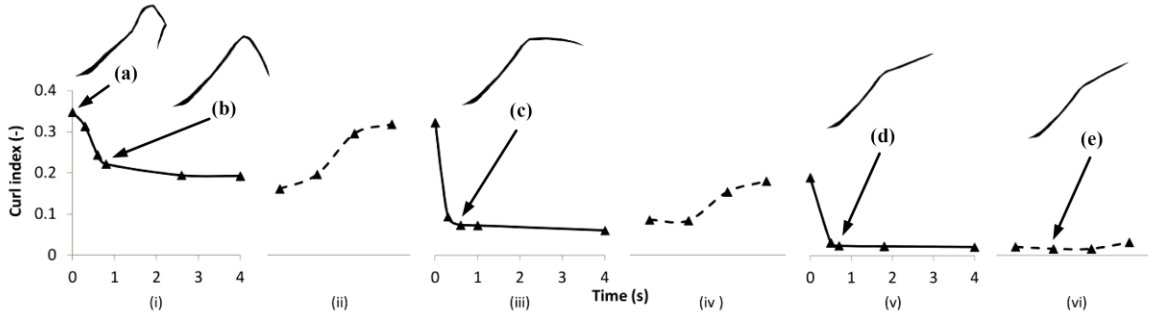

Fig 3.5 Representative result illustrating the effect of temperature on fibre straightening, characterized by curl index. Here the fibre is subjected to three temperature and moisture cycles, including (i) 23°C, (ii) air-dried, (iii) 50°C, (iv) air-dried, (v) 85°C, (vi) air-dried. Reproduced real fibre images added for selected points (a) - (e) shows clearly the process of fibre straightening.

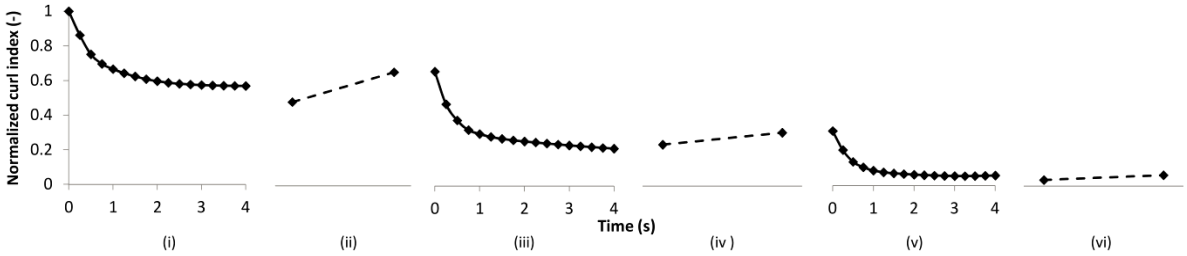

Fig 3.6 The effect of temperature on fibre straightening, characterized by curl index. Here the fibre is subjected to three temperature and moisture cycles, including (i) 23°C, (ii) air-dried, (iii) 50°C, (iv) air-dried, (v) 85°C, (vi) air-dried. Each data point shown in this figure represents an arithmetic average of curl index of six sample fibres.

3.3 Discussion

The first observation that can be made from these results is that both water uptake and temperature are significant factors in the overall forces which cause fibre straightening. Fibres deflect when absorbing room-temperature water but the deflection is limited. For permanent straightening, the temperature of the fibre must be raised above the glass transition point of the lignin. These findings are not new. What is interesting with this work, and what we feel has industrial significance is the rate at which permanent fibre straightening occurs. As seen in *Figs 3.3(iii), 3.4(iii), 3.5(v)* and *3.6(v)*, the fibres became straightened in approximately 1 second. This finding has implications of the efficiency of the industrial operation of latency removal, which currently has residence times of about half an hour.

Latency removal is the process that recovers the latent pulp properties, which involves both fibre deflocculation and fibre straightening. The key here is that latency removal is governed by a number of different mechanisms and the rate of each mechanism has not clearly been defined in the literature. At this point we define what we believe to be the key steps in this process and attempt to define the characteristic times over which these processes occur.
To begin, in a laboratory experiment we advance the argument that latency is removed in three key distinct steps:

(a) Water uptake by the fibre through which fibre straightening occurs. Our results in *Figs 3.3(i), 3.4(i), 3.5(i)* and *3.6(i)* indicate that fibre straightening induced by water uptake occurs over approximately 1-2 seconds.

(b) Heat transfer from the fluid to the fibre allowing the lignin and hemicelluloses matrix to relax. The characteristic time for this process is related very approximately to the thermal diffusivity and thickness of the fibre wall. If we assume the thermal diffusivity of a fibre to $1.6 \times 10^{-7} \sim 8.9 \times 10^{-8}$ m^2/s and the fibre wall thickness to 2.5 ~3.5 μm, values which are representative of Western hemlock, we see that the characteristic time to heat up the fibre to 85 ℃ is of the order of a millisecond.

(c) Fibre deflocculation which allows the fibres to straighten in an isolated state. There are no estimates in the literature for the hydrodynamic conditions in a latency chest. In the laboratory, we evaluated the latency removal of the pulp suspension at a power intensity a few times higher than that applied in an industrial latency chest, and found 30 minutes was not sufficient to obtain a complete fibre deflocculation if the mixing was carried out at room temperature. This length of time was substantially reduced to about 5 minutes when the treatment was carried out at a temperature of 85 ℃, but still much longer than 1 second, the time required for softening the lignin in an isolated fibre and the consequent fibre straightening.

From these estimates, we see that the different rate processes governing latency removal occur over timescales which are vastly different. Our results indicate that the straightening

process occurs at a much different rate than the deflocculation rate. Different from laboratory process, the initial heat transfer in industrial operation of latency removal is completed as early as in the refining process when the fibres are in contact with the steam. The major part of the steam is then removed in a steam separation unit and the fibres are travelling with a small portion of steam at a temperature of around 100 ℃, until they are transferred to the latency chest, where the temperature has been maintained around 80-85 ℃ and heat transfer takes place from fibres to water. No matter how many times the heat transfer occurs, it is a fast process and the length of time to achieve complete removal latency is still dependent on the time required to complete fibre deflocculation. The existence of non-ideal flow condition such as by-passing, recirculation and stagnant regions in the latency chest (Ein-Mozaffari *et al*. 2004) demands prolonged time to achieve complete latency removal. We advance the argument that, in both laboratory and industrial operation of latency removal, fibre deflocculation is the rate controlling step in the operation of latency removal. If completely deflocculated, latency could be completely removed in under a few seconds.

3.4 Conclusions

In this chapter we examined experimentally the straightening event of isolated never-dried high consistency mechanical pulp fibres undergoing heat and moisture treatments. We find that at room temperature, fibres deflect under during the uptake of water; however the extent of straightening is limited and the fibres returned to its original curliness to various magnitudes after removal of the water. Near the glass transition point of lignin, the fibres achieve their maximum straightening after approximately 1 second and the straightening was permanent.

Chapter 4: Kinetics of Latency Removal

The dependence of latency removal on key variables, i.e. disintegration temperature, energy input and consistency, has been reviewed and presented in Chapter 2. Based on the review and the analysis of the literature data for the development of a kinetic model of latency removal, this chapter has been focused on obtaining all the required experimental data and developing a kinetic model of latency removal, in terms of freeness.

A customized four-factor, i.e. disintegration temperature, power input, consistency and time, mixed-level factorial design was developed. The experimental data were obtained by changing one parameter at a time in each experiment so that the relationship of freeness-time, temperature-time, power intensity-time and consistency-time were easily established, and the unknowns in the proposed kinetic expression of latency removal were able to be determined using linear regression. In addition, a Matlab program was written to estimate the unknown parameters using non-linear regression.The kinetic study was carried out on both TMP and BCTMP pulps.

4.1 Material and Methods

The vessel used for the study is a fully baffled (four baffles with width of 1.9 cm) cylindrical vessel with diameter of 22.9 cm and height of 20.0 cm. A top entering geometrically scaled Maxflo impeller (Chemineer Inc., Dayton, OH) (3 bladed, diameter = 14 cm and pitch ratio = 0.44) was mounted on an instrumented shaft driven by a 0.25 kW variable speed motor with impeller off-bottom clearance maintained at 3.2 cm. The rotational speed was measured to ± 1 rpm using a photoelectric sensor and shaft torque was measured to ±0.002 Nm using an in-line strain gauge. A schematic of the experimental setup (vertical mixer) is provided in Appendix B.1.

The study on latency removal kinetics was carried out on never-dried secondary high consistency refining TMP and BCTMP pulps. High consistency (45%) Western hemlock TMP pulp was obtained from Howe Sound Pulp & Paper Ltd. (HSPP) and high consistency (25%) SPF (spruce (75%), pine (20%) and fir (5%)) BCTMP pulp was obtained from Quesnel River Pulp (QRP). Fibre lengths of each pulp sample were determined using

OpTest Fibre Quality Analyzer (FQA) after complete latency removal. The values of the mean lengths of TMP pulp are 0.862 mm (arithmetic), 1.947 mm (length weighted) and 2.376 mm (weight weighted), respectively. The mean lengths of BCTMP pulp are 0.894 mm (arithmetic), 1.601 mm (length weighted) and 2.255 mm (weight weighted), respectively.

Latency removal of primary high consistency (40%) refining pulp was carried out on never-dried SPF (spruce (75%), pine (20%) and fir (5%)) BCTMP pulp obtained from QRP with fibre mean lengths of 0.944 mm (arithmetic), 1.685 mm (length weighted) and 2.371 mm (weight weighted), respectively.

A series of batch experiments were designed. For each experiment, the TMP pulp sample was added to the preheated water to make a 5 L pulp suspension with designed temperature, i.e. 23, 40, 60 or 80°C, and consistency, i.e. 0.5, 1, 2, 3 or 4%. The suspension was then mixed at designed rotational speed, i.e. 600, 700, 800 or 900 rpm, for a certain length of time, i.e. 2, 5, 10 or 30 minutes. The power intensity calculated based on the rotational speed and the torque was 1.89, 2.64, 3.72 or 4.57 W/kg-suspension. In this project, the consistency of the pulp suspension studied was up to 5%. Since the treatments were carried out at low consistencies, the power intensity was calculated based on the weight of the suspension, rather than that of the fibre in the suspension. Detailed experimental conditions for the kinetic study of latency removal on TMP pulp are listed in *Table 4.1*. Upon the completion of the treatment, the suspension was quenched to 20°C and diluted to 0.3% with cold distilled water.

The freeness was measured according to TAPPI Standard T 227. Three replicate freeness tests on each treated pulp sample were carried out in order to determine the experimental errors, and the values reported in this paper are arithmetical averages.

Table 4.1 Summary of the experimental conditions for the kinetic study of TMP pulp

Consistency (%)		**0.5**	**1**													**2**			**3**			**4**
Power intensity (W/kg)		**3.72**	**1.89**				**2.64**				**3.72**				**4.57**	**3.72**			**3.72**			**3.72**
Temperature (°C)		**60**	**23**	**40**	**60**	**80**	**23**	**40**	**60**	**80**	**23**	**40**	**60**	**80**	**60**	**40**	**60**	**80**	**40**	**60**	**80**	**60**
Time (min)	**2**	*E1*			*E10*	E14			*E23*	*E27*			*E36*	E40	*E44*							
	5	*E2*		E7	*E11*	E15		*E20*	*E24*	*E28*		E33	*E37*	E41	*E45*	E48	*E51*	E54	E57	*E60*	E63	*E66*
	10	*E3*	E5	E8	*E12*	E16	*E18*	*E21*	*E25*	*E29*	E31	E34	*E38*	E42	*E46*	E49	*E52*	E55	E58	*E61*	E64	*E67*
	30	E4	E6	E9	E13	E17	*E19*	*E22*	*E26*	*E30*	E32	E35	E39	E43	E47	E50	E53	E56	E59	E62	E65	E68

4.2 Results

4.2.1 Kinetic Expression of Latency Removal of TMP pulp

The initial freeness value of the pulp F_0 was determined by direct measurement of the original untreated pulp sample. In this study the initial freeness has been determined as 820 mL. The final freeness value of the pulp F_f was determined as the constant value of the freeness when all the latency was removed. In this study F_f was determined as 220 mL, the freeness of the pulp sample being treated at a temperature of 80°C, consistency of 3% and power intensity of 3.72 W/kg-suspension for 30 minutes. The standard deviations were determined for each treated sample, with the highest value determined as 5 mL. Since the values were too small to discern the difference from one another when shown in the figures, no standard deviations were included in any figure illustrating the variation of freeness.

The time dependent latency releasing process is shown in *Fig 4.1*, which was characterized by the decrease of freeness at two different power intensities and four different temperatures. The initial rate drop in freeness was fast, but it slowed significantly as the treatment proceeded, which was more distinct at high temperatures. The sizes of fibre flocs in the originally highly flocculated pulp sample were seen to decrease rapidly in the first few minutes of the treatment, resulting in a rapid decrease in freeness. As the treatment continued, the freeness reached an asymptotic level, the so-called "floor-level" freeness, which was the characteristic freeness value for a pulp after all the latency has been removed. This value is expected to vary from pulp to pulp which was produced from different wood species and at different refining conditions.

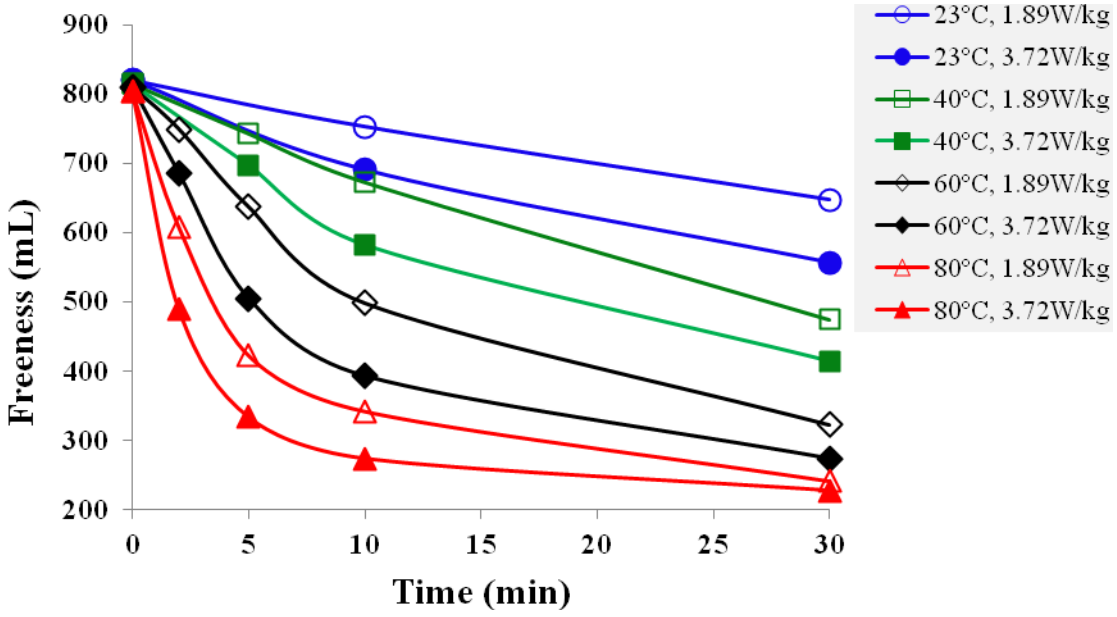

Fig 4.1 Latency releasing at different power intensities and temperatures. All the experiments were carried out at a consistency of 1%. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0% to 0.91%.

Based on the preliminary analysis on the literature data carried out in Chapter 2, the same kinetic expression (*Eq* 2.1) is proposed to model latency removal

$$-\frac{dF}{dt} = k \cdot \left(\frac{F - F_f}{F_0 - F_f} \right)^n$$

where

$$k = k_0 \cdot \exp\left(-\frac{\alpha}{T} \right) \cdot \varepsilon^{\beta} \cdot Cm^{\gamma} \qquad \textbf{(4.1)}$$

among which k and n are the rate constant and kinetic order of the model, respectively. Normalized freeness is used in the model expression, where F is the measured freeness, F_0 is the initial freeness, and F_f is the final freeness, the "floor-level" value to account for the existence of the residual freeness discussed above. The rate constant k is dependent on disintegration temperature of the treatment T, power intensity of the treatment ε, and pulp consistency Cm. k_0, α, β and γ are the overall constant, the exponential function constant, the order to the power-law function, and the order to the power-law function, respectively. There

are six unknowns, i.e. k, k_0, n, α, β and γ, in the kinetic expression. The integral method discussed in Chapter 2 was used to determine the kinetic order n and rate constant k.

When a value is assigned to the kinetic order, the model expression is able to be integrated, giving the solution as:

$$\begin{cases} \ln\left(\frac{F-F_f}{F_0-F_f}\right)_t - \ln\left(\frac{F-F_f}{F_0-F_f}\right)_0 = -\frac{k}{F_0-F_f}\cdot t & \text{(when } n=1\text{)} \\ \left(\frac{F-F_f}{F_0-F_f}\right)_t^{-n+1} - \left(\frac{F-F_f}{F_0-F_f}\right)_0^{-n+1} = -\frac{(1-n)\cdot k}{F_0-F_f}\cdot t & \text{(when } n\neq 1\text{)} \end{cases}$$

Theoretically, the kinetic order can be found when a linear plot between $\ln\left(\frac{F-F_f}{F_0-F_f}\right)_t$ and t (when $n=1$) or $\left(\frac{F-F_f}{F_0-F_f}\right)_t^{-n+1}$ and t (when $n\neq 1$) is obtained, from which the rate constant k can be determined. Practically, best linear relationship can be determined by comparing the R-squared values of the linear trendlines. The experimental data was divided into two groups, one (the italics in *Table 4.1*) for model development, and the other (the non italics in *Table 4.1*) for model validation. The complete set of experimental data (including freeness for this chapter and other pulp properties for the following chapter) is provided in Appendix B.2.

4.2.1.1 Effect of Disintegration Temperature

The change in freeness at different temperatures is plotted in *Fig 4.2*, which shows the difference in the rate of latency removal at different temperatures. In the initial phase (first five to eight minutes), the higher the disintegration temperature was, the faster the rate of latency releasing was.

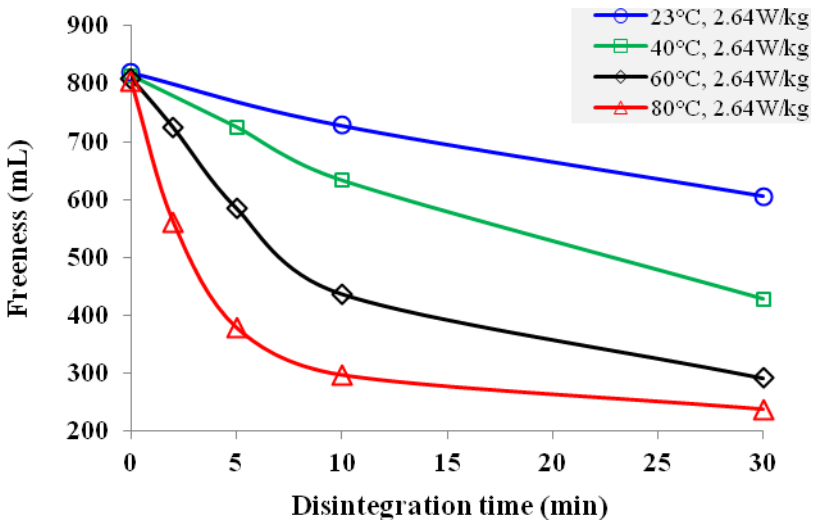

Fig 4.2 The decreasing of freeness in latency removal at different temperatures. All experiments were carried out at a consistency of 1%. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0% to 1.00%.

The experimental data was then analyzed to determine the unknowns, i.e. the kinetic order n, and the exponential function constant α. It is obvious that when keeping all others experimental conditions constant but changing the temperature only, the rate of change in freeness will be a function of temperature only. For clarification, a subscript $_T$ was added to the rate constant to represent the temperature dependence. An Arrhenius-type expression was explored as the formula for the temperature dependence of rate constant, which was expressed as

$$k_T = A_T \cdot \exp\left(-\frac{\alpha}{T}\right) \qquad \textbf{(4.2)}$$

When the kinetic order is determined as 1.5 by the integral method, the corresponding rate constant k_T at each temperature was determined, which was then plotted to evaluate the rate constant – temperature relationship. As shown in *Fig 4.3*, a linear relationship between $\ln k_T$ and $1/T$ was obtained, which verified that the Arrhenius-type expression for the temperature dependence of rate constant was appropriate for the kinetics of latency removal, where the numerical value of α was also determined as the slope of the trendline.

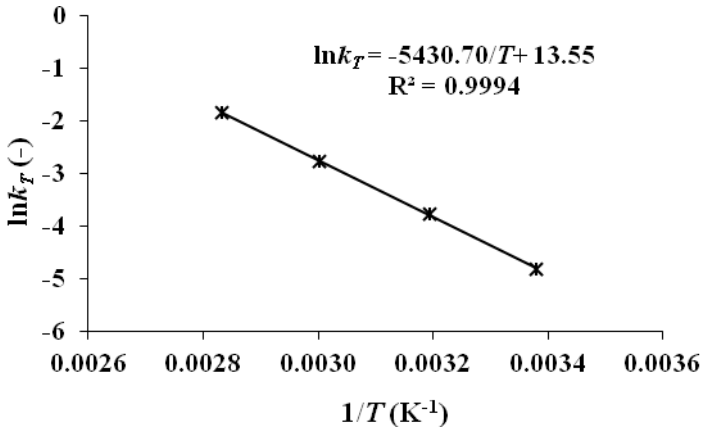

Fig 4.3 The linear plot between $1/T$ and $\ln k_T$ verified Arrhenius-type temperature dependence of rate constant.

4.2.1.2 Effect of Power Input

The effect of power input on the rate of latency removal is illustrated in *Fig 4.4*, showing that higher power input speeds up the rate of latency removal, which is more distinct in the first ten minutes of the treatment during which the majority of the latency is removed. The data was analyzed in terms of treatment energy as well (*Fig 4.5*), which shows that latency is continuously released as the treatment energy increases. The analysis on the effect of power and energy on latency removal suggests that the application of higher power shortens the time required to remove same amount of latency than lower power, which could potentially increase the production rate.

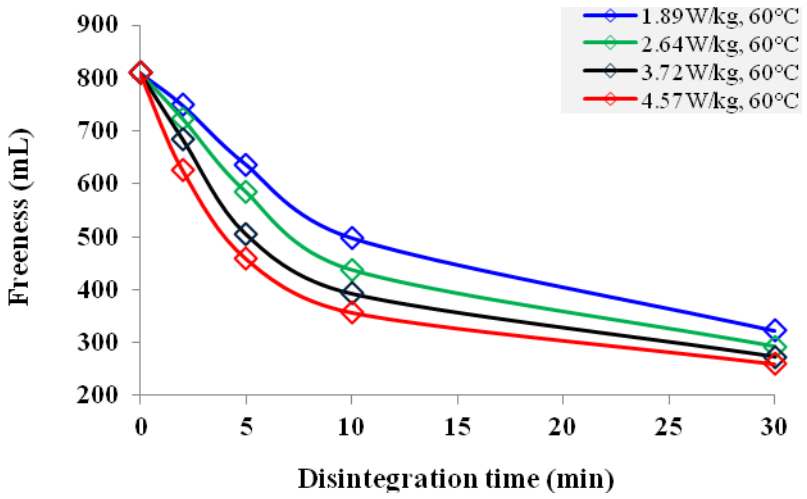

Fig 4.4 Latency releasing for pulp samples treated at different power intensities. All experiments were carried out at a consistency of 1%. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0.09% to 0.80%.

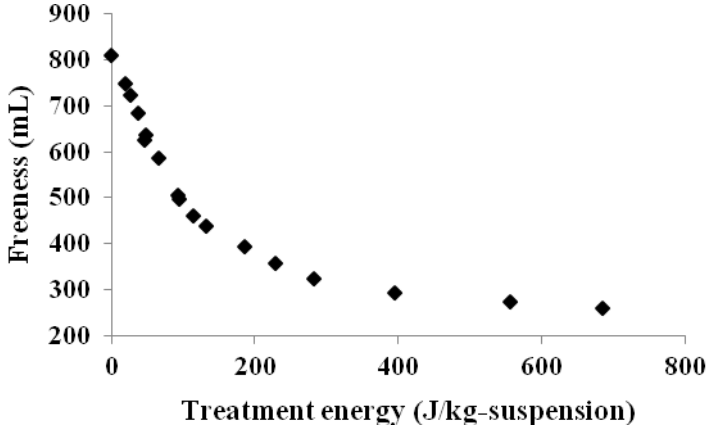

Fig 4.5 The relationship between treatment energy and latency releasing. All experiments were carried out at a consistency of 1% and a temperature of 60°C. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0.09% to 0.80%.

Similar analysis applied above was carried out to evaluate the effect of power input on latency removal and the rate constant k_ε at each power input was determined. A power-law formula was proposed for the dependence of the rate constant on power intensity, which was expressed as

$$k_\varepsilon = A_\varepsilon \cdot \varepsilon^\beta \qquad \textbf{(4.3)}$$

A linear relationship between lnk_ε and lnε was obtained (*Fig 4.6*). In consideration of the results shown in *Figs 4.5* and *4.6*, the value of β was determined as 1.

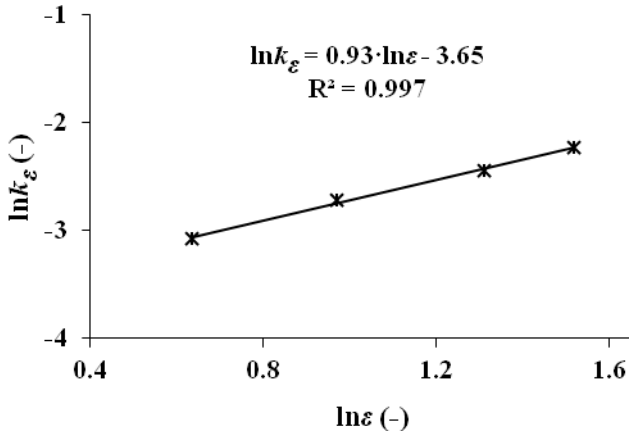

Fig 4.6 The linear plot between lnε and lnk_ε verifies the power-law dependence of rate constant on power input.

4.2.1.3 Effect of Consistency

Similar to the change of freeness at different power inputs, the rate of freeness releasing increased slightly as the pulp consistency increased from 0.5 to 4% at a constant power intensity of 3.72 W/kg-suspension (*Fig 4.7*), which occurred in the initial phase of the treatment. As the treatment proceeded, the fibre flocs were dispersed until all the fibres were unrestrained from the flocs and straightened, and the freeness reached the "floor-level" value, which remained constant with extended treatment time. Therefore, it is important to identify the right sampling time. If the sample was taken at which the latency has been completely removed, the result on the evaluation of the effect of consistency on latency removal would be misleading. This explains how the reported conclusions of no effect of consistency (up to 3 %) on latency removal (Beath *et al*. 1966; Dawson *et al*. 1978) were obtained.

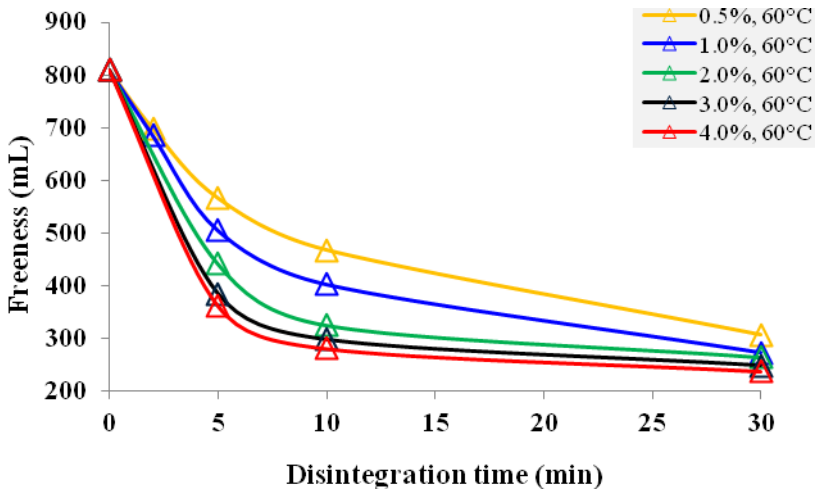

Fig 4.7 The decreasing of freeness in latency removal at different consistencies. All experiments were carried out at a power intensity of 3.72 W/kg-suspension. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0.09% to 1.79%.

A power-law formula was proposed for the dependence of the rate constant on consistency, expressed as

$$k_{Cm} = A_{Cm} \cdot Cm^{\gamma} \qquad \textbf{(4.4)}$$

A linear relationship between $\ln k_{Cm}$ and $\ln Cm$ was obtained (*Fig 4.8*), from which the value of γ was determined as 0.6.

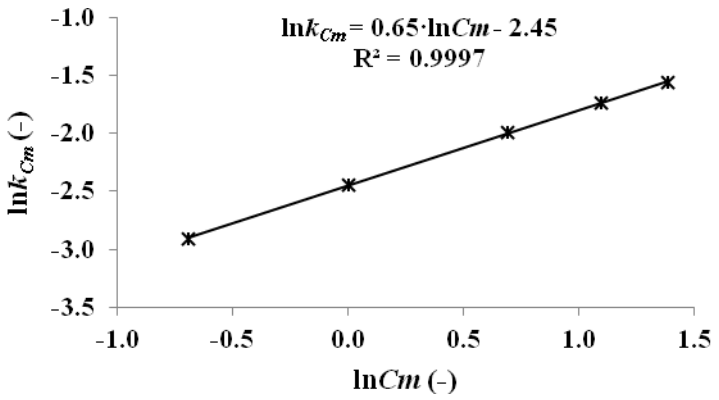

Fig 4.8 The linear plot between ln*Cm* and lnk_{Cm} verified power-law dependence of rate constant on consistency for consistencies up to 4%.

4.2.1.4 Kinetic Expression

With the determination of kinetic order *n*, the exponential function constant α, and the orders to the power-law function β and γ, we obtained the complete kinetic expression of latency removal as:

$$-\frac{dF}{dt} = 3.60\times10^{8}\cdot\exp\left(-\frac{5430}{T}\right)\cdot\varepsilon\cdot Cm^{0.6}\cdot\left(\frac{F-F_f}{F_0-F_f}\right)^{1.5} \qquad \textbf{(4.5)}$$

The model was then verified by comparing the predicted freeness values calculated using the model and the measured values for the experimental data group (the non italics in *Table 4.1*) that hasn't been used for the model development. As presented in *Fig 4.9*, the data are close to the 45° straight line, which concludes that the developed kinetic model predicts well the process of latency removal, characterized by freeness.

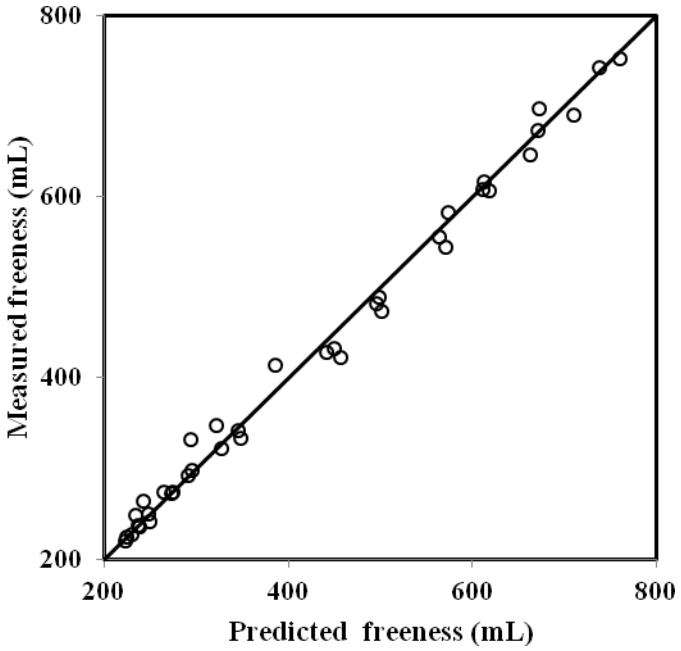

Fig 4.9 Model validation through comparing of experimentally measured and model predicted values of freeness.

In addition to the mathematical derivation, a Matlab program was written to determine the unknowns in the kinetic expression that best fits the experimental data. Based on the Nelder-Mead optimization method, the Matlab function *fminsearch* was applied to find the optimum set of parameters that minimizes the discrepancy between the experimental data and the model's predictions and brings the model's predictions as close as possible to the experimental data. The program code is provided in Appendix C. A set of parameters was obtained and the model was determined as

$$-\frac{dF}{dt} = 3.95\times10^{8}\cdot\exp\left(-\frac{5502}{T}\right)\cdot\varepsilon\cdot Cm^{0.6}\cdot\left(\frac{F-F_f}{F_0-F_f}\right)^{1.3} \qquad \textbf{(4.6)}$$

which is in a good agreement with the equation (*Eq 4.5*) derived mathematically.

In the operation of latency removal, mechanical pulp mills employ higher temperature and consistency, i.e. consistency of 5% and temperature of 85°C, than the temperatures and consistencies applied for the model development in this study. To check if the model is applicable for industrial operation conditions, an experiment was carried out and the result

was compared with the predicted result using the model. As shown in Table 4.2, the kinetic model predicted the experimental result nicely and validated itself as a satisfying tool for the prediction of freeness change in latency removal. Higher power intensity was applied for the treatment and its effect on latency removal with respect to energy savings will be discussed later in this chapter.

Table 4.2 Model validation at industrial operation conditions

Temperature (°C)	Consistency (%)	Power intensity (W/kg-suspension)	Time (min)	Measured freeness (mL)	Predicted freeness (mL)
85	5	9.60	2	248	241

4.2.2 Kinetic Expression of Latency Removal of BCTMP pulp

A similar analysis was carried out on never-dried secondary high consistency BCTMP pulp (experimental data are listed in Appendix D). The effects of disintegration temperature, power intensity and consistency on latency removal of the pulp and the analysis to determine the mathematical expression for each factor in the kinetic model are presented in *Fig 4.10 – 4.15*.

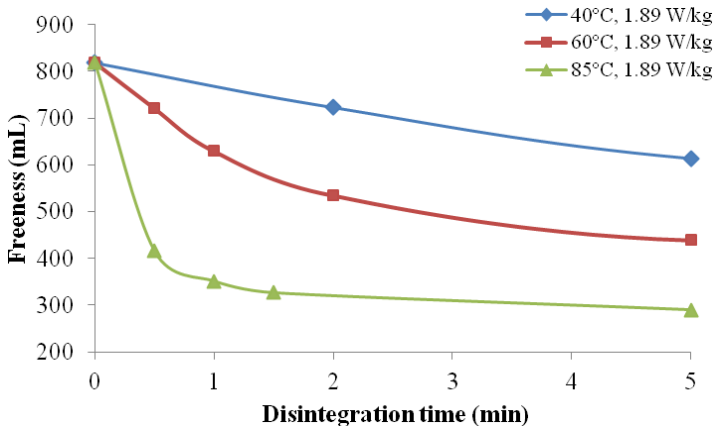

Fig 4.10 The decreasing of freeness in latency removal at different temperatures. All experiments were carried out at a consistency of 1%. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0.11% to 1.80%.

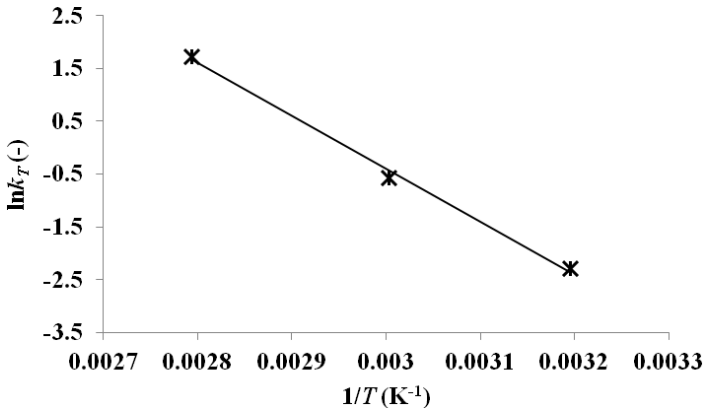

Fig 4.11 The linear plot between 1/T and lnk_T verified Arrhenius-type temperature dependence of rate constant.

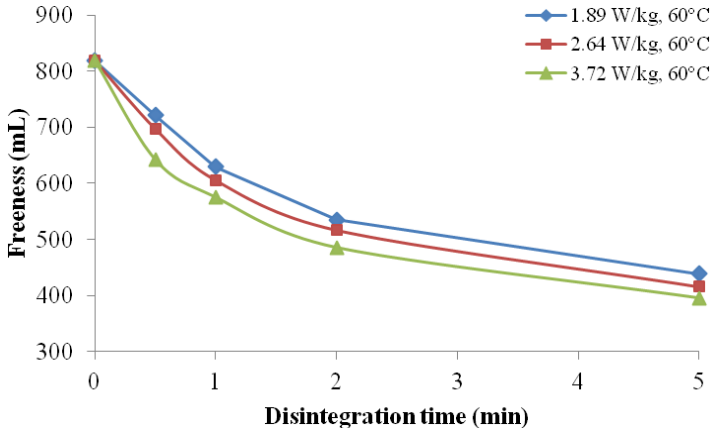

Fig 4.12 Latency releasing for pulp samples treated at different power intensities. All experiments were carried out at a consistency of 1%. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0.11% to 1.09%.

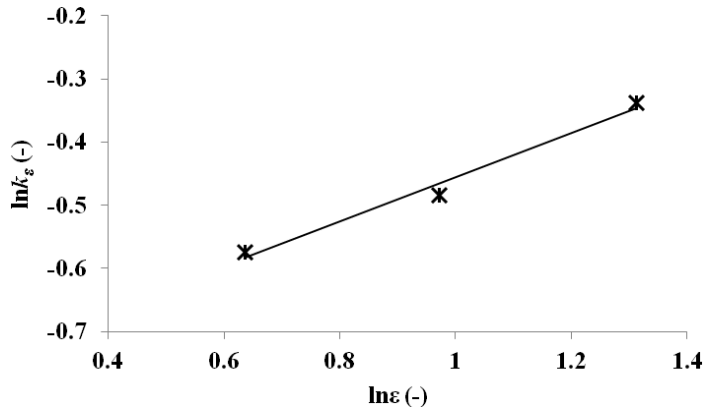

Fig 4.13 The linear plot between lnε and lnk_ε verifies the power-law dependence of rate constant on power input.

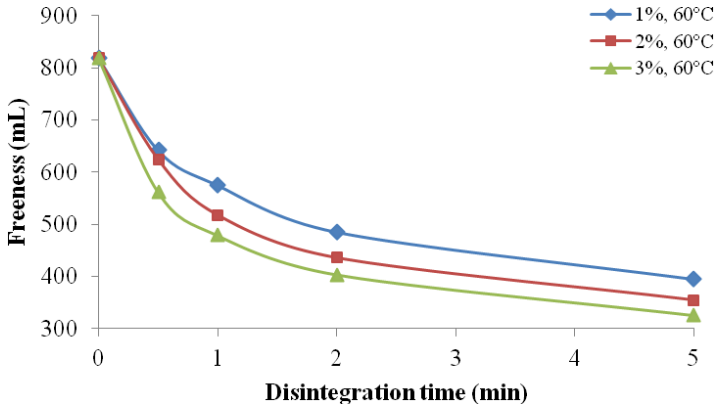

Fig 4.14 The decreasing of freeness in latency removal at different consistencies. All experiments were carried out at a power intensity of 3.72 W/kg-suspension. All freeness values in the figure were arithmetical averages of results of three replicate tests and the relative standard deviations calculated were ranged from 0.11% to 0.81%.

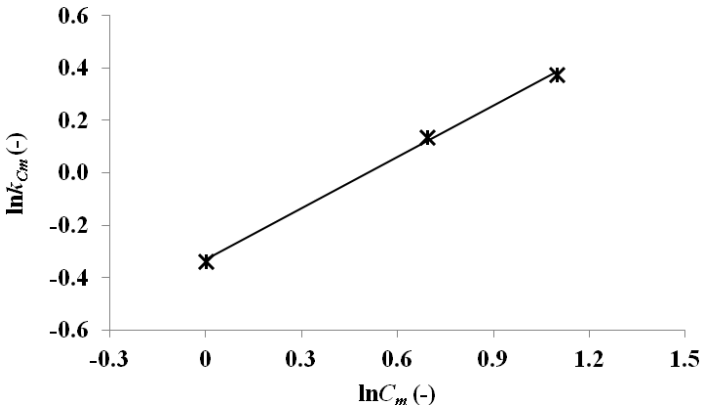

Fig 4.15 The linear plot between ln*Cm* and lnk_{Cm} verified power-law dependence of rate constant on consistency for consistencies up to 3%.

The kinetic expression of latency removal of BCTMP pulp obtained by mathematical derivation is

$$-\frac{dF}{dt} = 3.10\times10^{15}\cdot\exp\left(-\frac{10017}{T}\right)\cdot\varepsilon^{0.4}\cdot Cm^{0.7}\cdot\left(\frac{F-F_f}{F_0-F_f}\right)^2 \qquad \textbf{(4.7)}$$

The experimental data were then analyzed using the same Matlab program written for the TMP pulp, which was presented in Appendix C. The expression determined is

$$-\frac{dF}{dt} = 3.92\times10^{14}\cdot\exp\left(-\frac{9359}{T}\right)\cdot\varepsilon^{0.38}\cdot Cm^{0.62}\cdot\left(\frac{F-F_f}{F_0-F_f}\right)^{1.9} \qquad \textbf{(4.8)}$$

The expressions obtained by mathematical derivation and Matlab program show a good agreement and both work well in the predicting the change of freeness in latency removal (*Fig 4.16*).

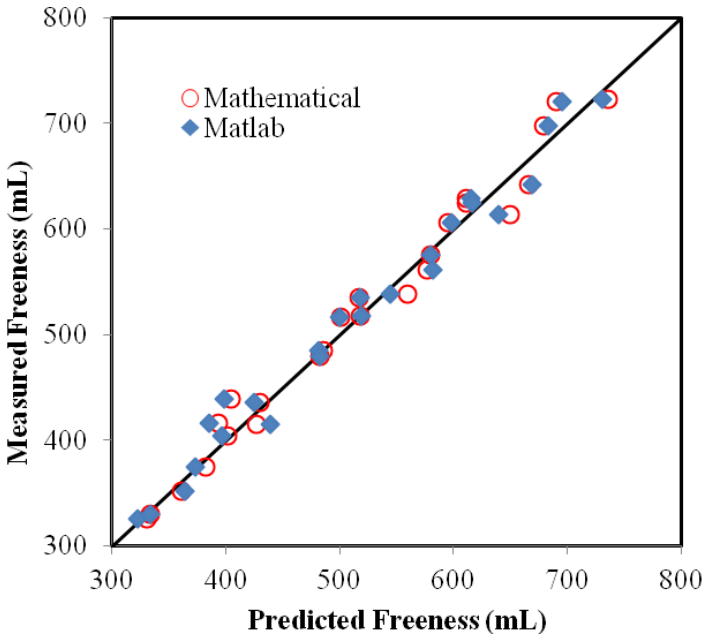

Fig 4.16 The comparison between the models determined mathematically and using the Matlab program in predicting the change of freeness in latency removal of BCTMP pulp.

In comparison with TMP pulp, latency removal of BCTMP pulp is faster. This is not only observed in the experiment but also evidenced by the higher rate constant in the kinetic expression of latency removal of BCTMP pulp. The lignin sulfonation occurred in chemical pretreatment results in the weakening of the lignin-hemicellulose matrix through weakening the interactions of the lignin-pectin, lignin-protein and pectin-protein bonds (Stevanic and Salmén 2007), which consequently improves fibre flexibility and fibre swelling as well as lowering the lignin softening temperature (Atack *et al*. 1978; Htun *et al*. 1988). As discussed previously, the rate of latency removal is dominantly controlled by fibre deflocculation. Therefore, it is believed that the fibre changes caused by lignin sulfonation results in a weaker fibre network, making the fibre deflocculation process much easier than that of TMP pulp.

4.3 Discussion

At initial stage of experimental design, it has been thought to isolate temperature from mechanical action, and to evaluate the effect of temperature on latency removal by heating the pulp at designed temperatures but without agitation. However, the results of a few trials showed that only a small portion of latency (less than 8% drop in freeness) was able to be removed for heating the pulp at a constant temperature of 85°C for as long as 30 minutes, which was thought to be resulted from the fibre straightening of those isolated fibres and the free ends of the fibres in the fibre flocs. This suggests that fibre deflocculation is an indispensable process in the operation of latency removal and it is more practical to evaluate the effect of temperature with the addition of agitation.

As previously discussed, freeness is influenced by fines content. In order to determine the effect of fines content in latency removal, the fines content, measured by FQA, was plotted at different treatment conditions. According to the result (*Fig 4.17*), the fines contents measured were not dependent on the treatment conditions. This helps to verify that latency removal is a gentle mechanical treatment during which the fibres mainly change their morphology through fibre deflocculation and fibre straightening, rather than changing their surfaces and lengths during intense treatment such as refining during which the fines content changes greatly.

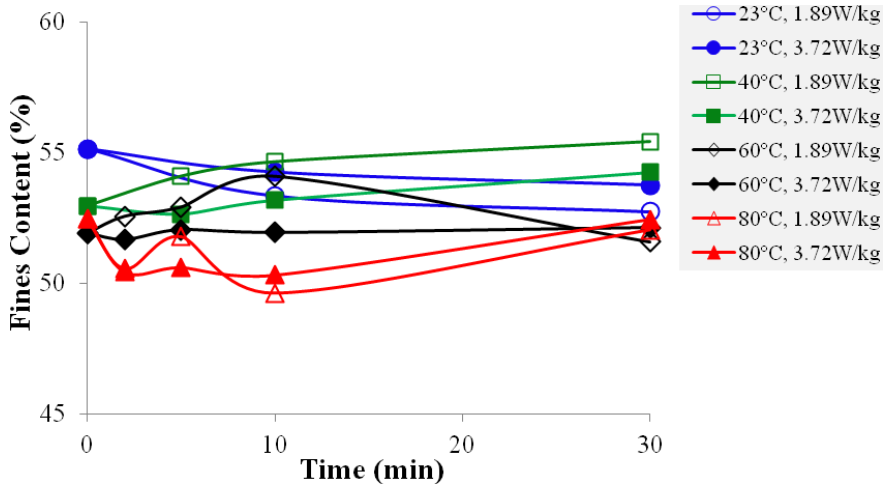

Fig 4.17 The change of fines content at different power intensities and temperatures. All the samples for the FQA measurement were treated at a consistency of 1%.

Operational Criteria of Latency Removal Process

The kinetic model expression suggests that, during the operation of latency removal, the temperature at which the disintegration is carrying out should be as high as possible. Higher temperature will not only effectively remove latency but also speed up the process. During the experiment, it has also been noted that bubbling occurred in the pulp suspension at temperatures near the water boiling point compromised the effectiveness of the treatment, which advises that the operation temperature should be maintained below water boiling point.

As mentioned previously, increasing power intensity of the mixing in the latency chest would reduce the time required to remove all the latency, which provides an opportunity to increase the production rate, but at a cost of higher energy consumption. Yet, after comparing the total mechanical energies between the laboratory experiment on latency removal at 5% (*Table 4.2*) at a higher power intensity and mill operation at a lower power intensity, we found that laboratory experiment removed same amount of latency with less energy consumption. This promising result shows that applying higher power intensity in the operation of latency is beneficial if appropriate operational conditions are applied, which will not only reduce the mechanical energy consumption but also increase the production rate, leading to higher return on investment.

4.4 Conclusions

For latency removal of both TMP and BCTMP pulps at a temperature higher than lignin softening temperature, the release of latency proceeded rapidly in the initial phase followed by the second phase, in which the freeness releasing rate was much slower and approached asymptotically to a "floor level". The kinetic expression of latency removal for secondary refiner TMP and BCTMP pulps have been shown to follow a one-and-a-half order and a second order, respectively, involving disintegration temperature, pulp consistency and power intensity of the treatment. Resulting from lignin sulfonation, complete latency removal of BCTMP pulp requires less time than TMP pulp at same treatment energy. The analysis reveals that the potential to optimize current operation of latency removal in the pulp mills and energy reduction can be achieved by applying higher power intensity in the operation of latency removal.

Chapter 5: Potential Application of the Kinetic Model in Characterizing Industrial Latency Removal Process

5.1 Modelling Mixing Zone

The latency chest is typically operated in a zone-agitation mode, where good mixing in the agitation zone and poor mixing outside the agitation zone exist simultaneously. The multiple-impeller latency chest has very complicated flow dynamics and it is difficult to simulate the mixing in the chest. To simulate such a system, it is required to determine the models for the perfectly mixed region and the non-perfectly mixed region and establish an expression to combine them together.

For the mixing zone, we have developed a model for latency removal and determined the specific rate constant *k* using the laboratory-scale batch "reactor", which is ready to be used in modeling the continuous stirred mixing zone. Considering latency removal as a hypothetical reaction in which pulp suspension loses its freeness in a way that is characterized by the developed kinetic model of latency removal presented in Chapter 4, we could use the knowledge and the designing equations available in chemical reaction engineering to design the mixing zone in the latency chest.

The first step is to review the development of the designing equations for reactor design in chemical engineering. For a second-order liquid-phase reaction being carried out in a continuous stirred-tank reactor, the combination of the rate law and the design equation yields:

$$V = \frac{F_{A0} - F_A}{-r_A} = \frac{\nu_0 \left(C_{A0} - C_A\right)}{kC_A{}^2} \qquad \textbf{(5.1)}$$

or in terms of mean residence time τ:

$$\tau = \frac{V}{\nu_0} = \frac{C_{A0} - C_A}{kC_A{}^2} \qquad \textbf{(5.2)}$$

where r_A is the rate of reaction; k is the rate constant; V is the volume of the reactor; F_{A0} and F_{A0} are the initial molar flow rate and molar flow rate of species A, respectively; C_{A0} and C_A are the initial concentration and local concentration of species A, respectively; ν_0 is the volumetric flow; and τ is the mean residence time.

For a one-and-a-half-order reaction, the designing equation obtained is

$$\tau = \frac{C_{A0} - C_A}{k\left(C_A\right)^{1.5}} \tag{5.3}$$

To model the mixing zone in latency chest of TMP pulp, it is required to replace the *k* in *Eq 5.3* with rate constant *k* of the kinetic model of latency removal of TMP pulp developed in this study, and replace C_A and C_{A0} with $\left(F - F_f\right)/\left(F_0 - F_f\right)$ and $\left(F_0 - F_f\right)/\left(F_0 - F_f\right) = 1$, respectively. This gives the model expression for the TMP pulp as

$$\tau = \frac{1 - \dfrac{F - F_f}{F_0 - F_f}}{3.4\times10^{8} \cdot \exp\left(-\dfrac{5430}{T}\right) \cdot \varepsilon \cdot Cm^{0.6} \cdot \left(\dfrac{F - F_f}{F_0 - F_f}\right)^{1.5}} \tag{5.4}$$

and for CTMP pulp, the model expression is

$$\tau = \frac{1 - \dfrac{F - F_f}{F_0 - F_f}}{3.1\times10^{15} \cdot \exp\left(-\dfrac{10017}{T}\right) \cdot \varepsilon^{0.4} \cdot Cm^{0.7} \cdot \left(\dfrac{F - F_f}{F_0 - F_f}\right)^{2}} \tag{5.5}$$

To find out the drop in freeness along with the mean residence time within the mixing zone, the Matlab *ezplot* function was used to generate the figures for *Eqs 5.4* and *5.5*. The program code with the details of the operation of latency removal carried out in HSPP and QRP was presented in Appendix E. The result (*Fig 5.1*) shows that latency is removed in much shorter time in comparison with the typical 20-60 minutes (for TMP pulp) or a few minutes (for CTMP pulp) residence time for the operation of latency remove in the pulp mills. Prolonged time is required for removing latency of the pulp suspension outside the mixing zone.

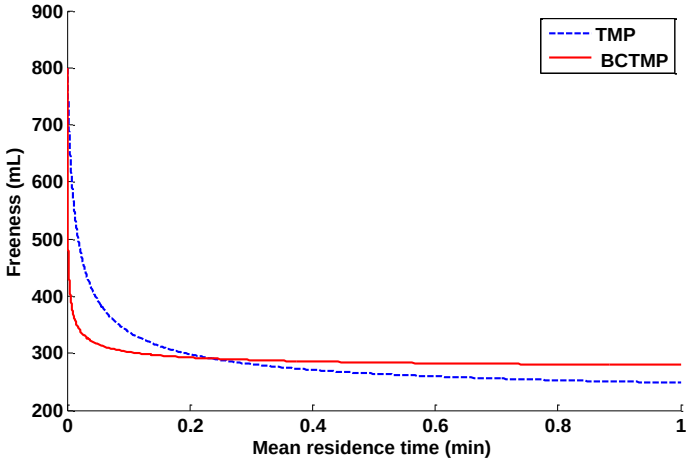

Fig 5.1 The rate of latency removal for the pulp suspension within the mixing zone.

5.2 Mixing Rule

In order to model latency removal process in the latency chest, a link between the fast latency releasing rate in the mixing zone and the slow latency releasing rate outside the mixing zone should be established so that the overall model expression can be determined. In a study of freeness prediction of pulp mixtures, Paulapuro (1977) developed a logarithmic mixing model for groundwood pulp mixtures. The logarithm of the freeness of a compound pulp is calculated in an additive way from the products of component weight proportion and the logarithmic of the component freeness value, which is expressed as

$$\ln CSF = \sum_{i=1}^{n} x_i \ln CSF_i \qquad \textbf{(5.6)}$$

where x_i is the weight proportion of the component pulp i in the pulp mixture.

The freeness values calculated using the model have been found in very good agreement with the measured values. The model was then applied by Tervaskanto *et al.* (2003) to model compound pulp quality of both TMP and CTMP pulp mixtures in the screening process in the pulp mills. Although the calculation using the model was affected by many factors, e.g. the existence of submodels, the different consistency regions, etc., the results have shown that the estimated compound freeness was more reliable than the on-line freeness measurement. In this part of study, experiments were carried out to simulate the mixing of pulp suspensions in the mixing zone and outside the mixing zone.

5.2.1 Materials and Methods

Two series of experiments were carried out on the secondary TMP pulp sample at a temperature of 23°C, a consistency of 1% and power intensity of 3.72 W/kg-suspension. Series 1 starts with the treatment of 3 kg untreated pulp suspension for 10 minutes, followed by adding 2 kg of 1% untreated pulp suspension and mixing the 5 kg pulp suspension for 10, 30 or 50 minutes. Series 2 starts with the treatment of 3 kg untreated pulp suspension for 30 minutes, followed by adding 2 kg of 1% untreated pulp suspension and mixing the 5 kg pulp suspension for 10 or 30 minutes.

5.2.2 Results and Discussion

The change in freeness for both series, and the calculated freeness values using the mixing rule and the kinetic model are presented in *Fig 5.2*. For either series, step one of the treatment partially removed the latency and lowered the freeness. The following step of adding 2 kg original untreated pulp suspension resulted in a pulp mixture with higher freeness due to the introduction of some latent pulp into the system. And then the treatments of the pulp mixture removed latency to various extents, depending on the length of the time of the treatment. Obviously the change in freeness in step one in either series can be predicted using the kinetic model of latency removal. But the key finding here is that in the following treatment, both the mixing rule and the kinetic model accurately predicted the initial freeness of the pulp mixture and the freeness changes after the treatments, respectively. When the freeness values for all the treatments was normalized and re-plotted, the curves (*Fig 5.3*) overlapped, which validates the application of the kinetic model of latency removal in modeling latency removal in industrial environment. Although current test has been limited to only one temperature and consistency condition, the result deserves a systematic study in the future work.

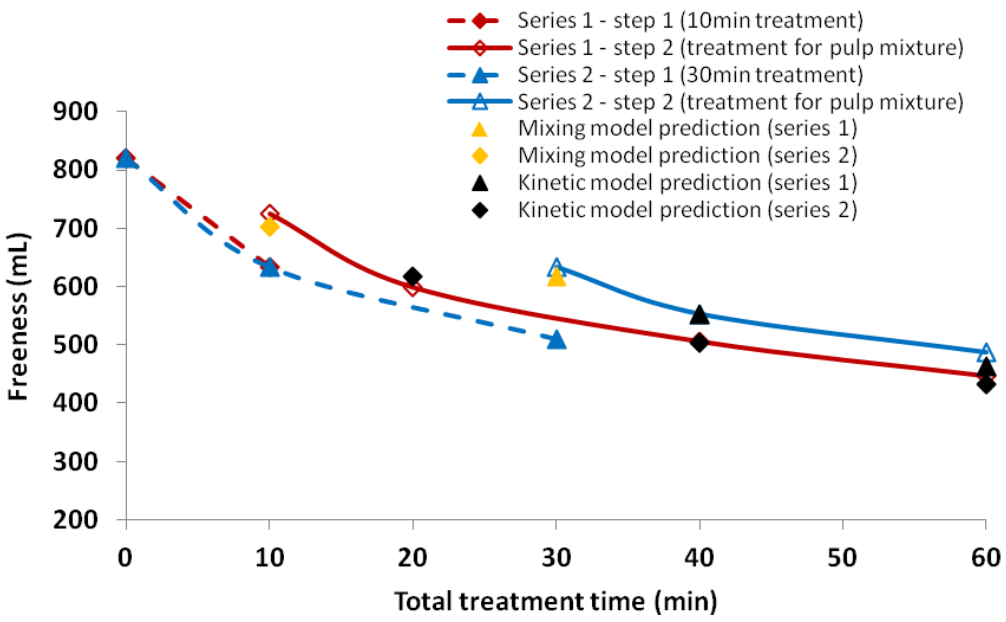

Fig 5.2 Laboratory study on the prediction of the change of freeness for pulp mixture using mixing rule and kinetic model of latency removal.

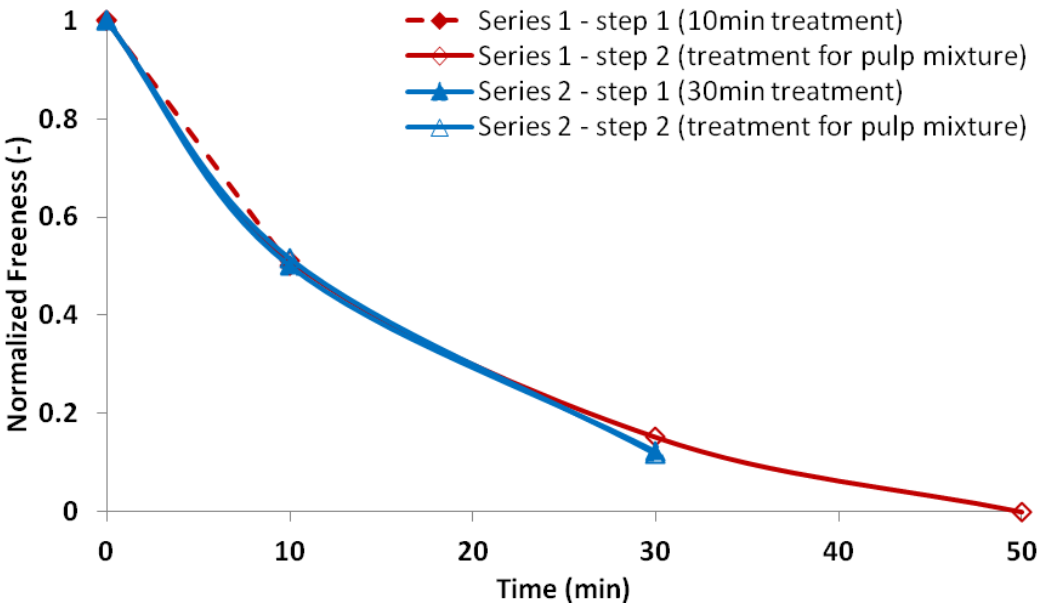

Fig 5.3 Laboratory study on the change of freeness in the treatment of pulp mixture.

Chapter 6: Characterizing Latency Removal by Fibre Curl and Strength Properties

As discussed in previous chapter, latency removal can be well characterized by freeness. Although freeness has been widely accepted as a good pulp property in measuring latency removal, it is not a direct measurement. Since the phenomena of latency is essentially resulted from fibre deformation, the most direct pulp property reflecting latency is fibre curl. In addition, freeness is not a conserved pulp property, which limits the use of freeness to be a useful parameter in modeling latency removal in a latency chest. Theoretically, the fibres will return to their straightened shape when the latency is completely removed, which makes fibre curl conserved property to characterize latency removal and a better pulp property in terms of interpreting the phenomena of latency removal.

The studies on latency removal characterized by fibre curl have been reviewed and presented in Chapter 2 and 3. In this chapter, we examine fibre curl in characterizing latency removal. In addition, the strength properties including tensile strength and tear strength are determined and the relationships between freeness and these properties are explored.

6.1 Materials and Methods

The same TMP pulp used in the kinetic study presented in previous chapter was used in this study. For each latency removal treatment described in Table 3.1, the curl index, tensile strength, tear strength and other pulp properties were measured along with the measurement of freeness. The curl index and fibre length were measured using FQA. The handsheets were made and prepared for measurement according to TAPPI Standards T 205 and T 220, and the tensile and tear strengths were measured according to TAPPI Standards T 494 and T 414, respectively.

6.2 Results

6.2.1 Change in Fibre Morphology, Characterized by Curl Index

The change in curl index of the TMP pulp sample treated at same consistency, but different temperatures and power intensities is presented in *Fig 6.1*. The results show that, for the treatment for 10 minutes or longer, fibre curl is influenced solely by temperature, and the

effect of power intensity is negligible. This conclusion is in support of the mechanism of fibre straightening in latency removal presented in Chapter 3 that fibre straightening is resulted from lignin softening which depends on the temperature at which the pulp sample is treated. Whereas, it is difficult to explain the change in curl index for the pulp samples treated for less than 5 minutes at all temperatures and the samples treated at 23°C at every sampling times.

Latency removal is a process during which highly flocculated and deformed fibres are dispersed and straightened. As a result, it is expected that the curl index would decrease or remain constant along with the time of treatment, rather than continuously increasing as observed for the treatment at 23°C or increasing followed by decreasing as observed for the treatment at 40 and 60°C. The confusing behavior is suspected to be related to the remaining fibre flocs in the treated pulp samples, which were observed after the treatments but removed before the measurements of curl indices. A comparison of two pulp samples which have treated at different conditions shows the remaining fibre flocs in the treated pulp sample (*Fig 6.2*).

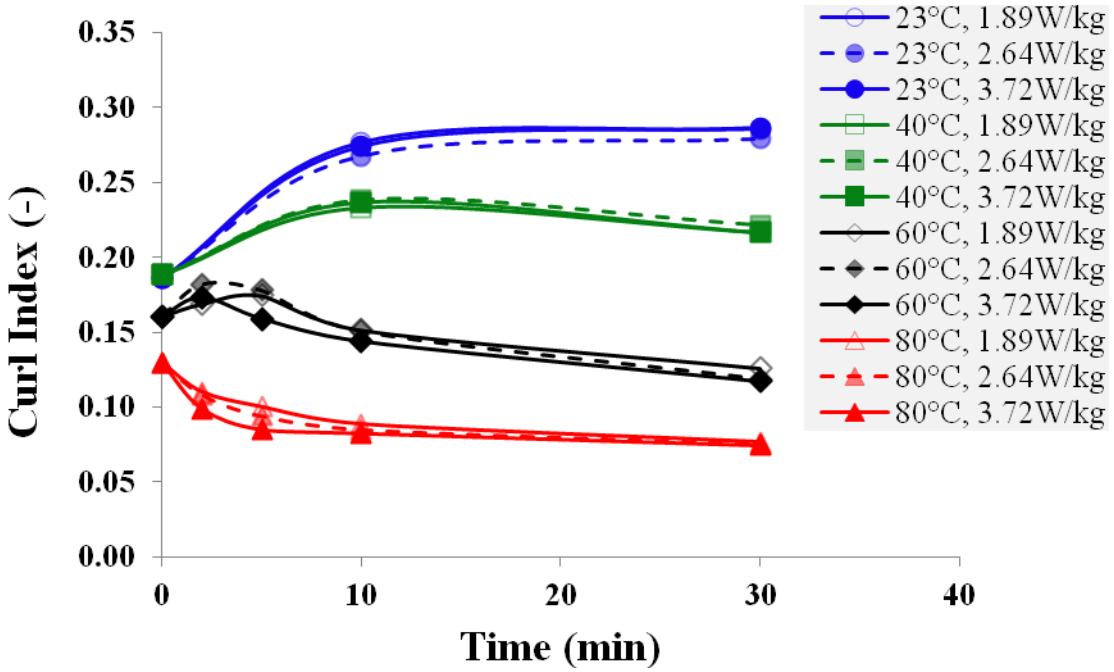

Fig 6.1 The change of curl index at different temperatures and power intensities showed its sole dependency on temperature after the pulp was dispersed. Experiments were carried out at a consistency of 1%.

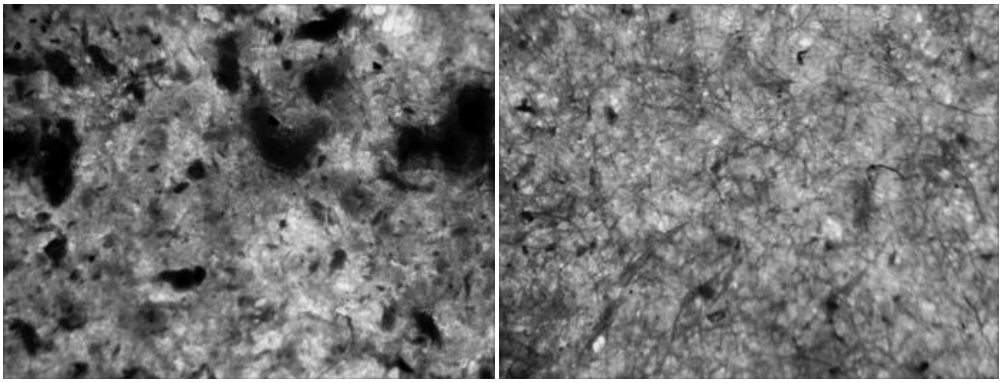

Fig 6.2 The comparison of the handsheets made from pulp treated at 40°C (left) and 80°C (right) shows that some fibre flocs (dark areas in left image) remained intact after the treatment. Both of the pulp samples were treated at a power intensity of 2.64 W/kg-suspension and a consistency of 1% for 10 minutes.

In order to determine the cause of the unexpected result shown in *Fig 6.1*, experiments on the effect of temperature on curl index for the pulp suspensions treated at different conditions were designed and conducted. The treatments include "Direct" treatment and "Deflocculation" treatment. In a "Direct" treatment the pulp sample was added directly to the water at a designed temperature and a consistency of 1% and gently stirred for a few seconds. While in a "Deflocculation" treatment the original pulp sample was disintegrated in a British Standard Disintegrator at a temperature of 20°C and a consistency of 0.3% for 5 minutes. "Prior" deflocculation was carried out before the "Direct" treatment and "Post" deflocculation was carried out after the "Direct" treatment. A schematic diagram (*Fig 6.3*) shows the morphological changes of fibres under each type of treatment.

The "Direct" treatment was carried out on three pulp samples including original untreated pulp sample, "Prior" deflocculated pulp sample and "Screened" pulp sample, the floc-free fibres obtained by screening the original pulp sample using a mesh sized 0.84 mm. As shown in *Fig 6.4*, the "Screened" pulp gave the lowest values of curl index at different temperatures, which were less dependent on the change of temperature. Observed from the experiment, the "Screened" fibres are isolated fibres which are less deformed. As a result, there was minor difference in the values of curl index when these relatively straight fibres were treated at different temperatures. When the "Direct" treatment was carried out with originally highly flocculated pulp sample, only the isolated fibres in the pulp sample were allowed to deflect,

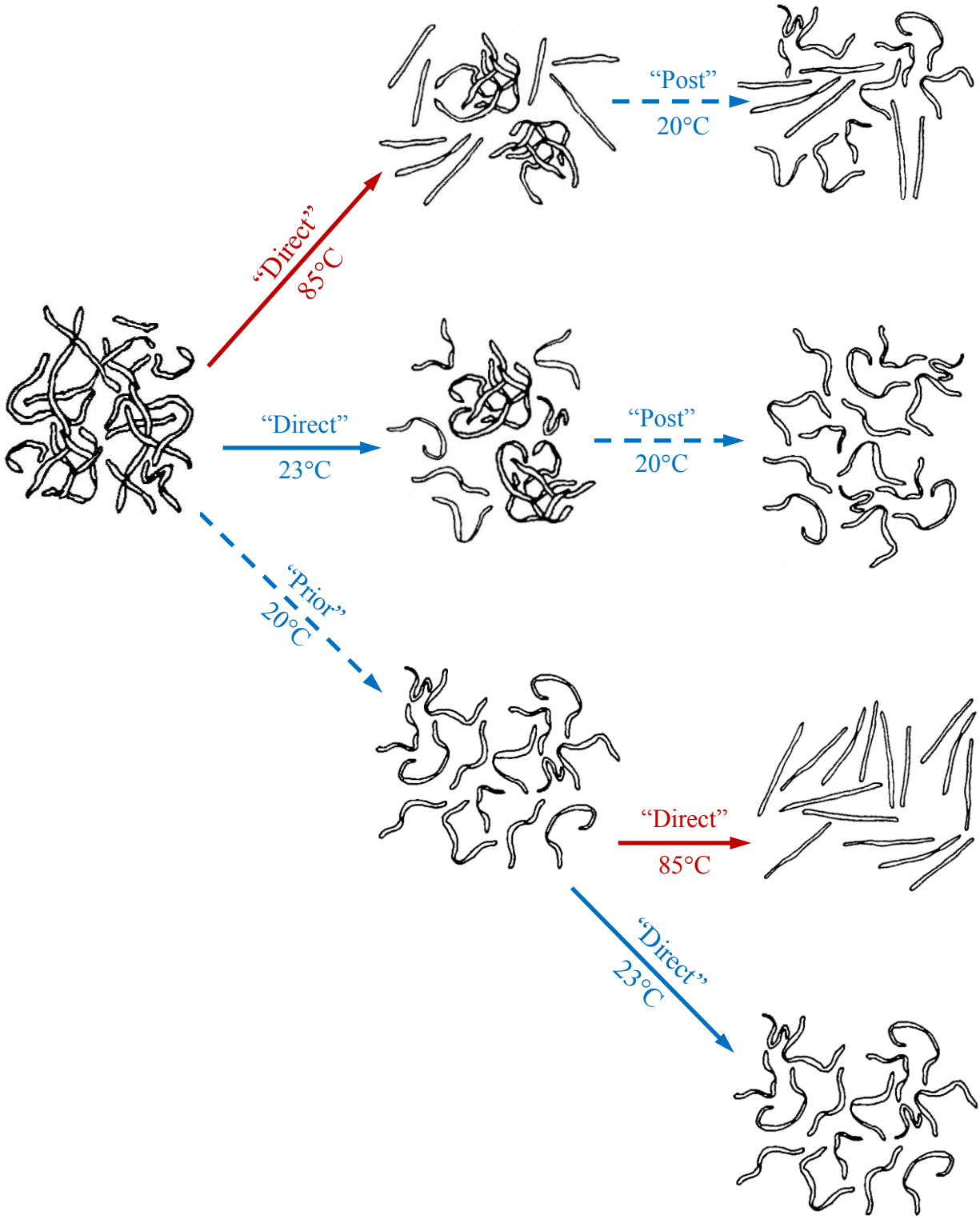

Fig 6.3 The change of fibre morphology under different treatment conditions. Red arrows represent the treatment at high temperature and blue arrows represent the treatment at low temperatures. Dash lines represent the treatment conducted in a British Standard Disintegrator. Necessary thickening is conducted for the treatment on the "Prior" treated pulp samples. The drawings of the fibres are modified from Mohlin 1980.

leaving all the fibre flocs unchanged, or to be precise, slightly changed as the free ends of the fibres in the flocs were able to deflect. When the treated sample was diluted for the measurement of curl index, it is unavoidable to introduce certain amount of fibre flocs, resulting in higher values in curl index at all temperatures according to the result shown in the figure, but similar trend as that of "Screened" pulp. Neither the "Screened" nor "Direct" treatment is suitable to be used for the characterization of the effect of temperature on curl index. Since the former neglected the dominating amount of highly deformed fibres in the fibre flocs in the pulp sample, while the latter is limited by the requirement of curl measuring equipment. Therefore, the pulp sample has to be deflocculated, if there is a large amount of fibre flocs present in the pulp sample, so that the true value of the curl index is able to be determined.

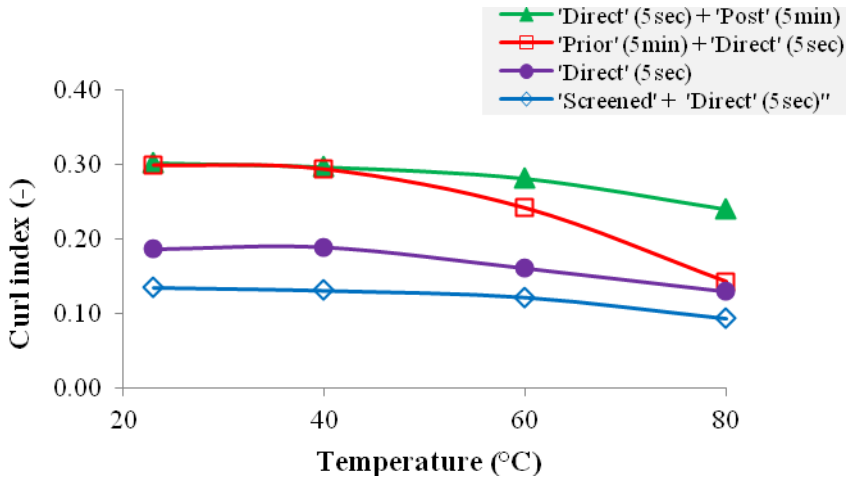

Fig 6.4 The change of curl index of pulp samples treated at different conditions.

Deflocculation experiment, performed in a British Standard Disintegrator at 20℃ for 5 minutes, has been found to have insignificant effect on curl index, but effectively remove fibre flocs. When a "Prior" deflocculation was conducted for the original pulp sample, the fibre flocs in the pulp sample were dispersed and all the fibres were free from restraint. As expected, the highly deformed but dispersed fibres then underwent the same change in morphology as that occurred to the isolated fibres discussed in Chapter 3, which were strongly influenced by the temperature at which the sample was treated. "Prior" deflocculation treatment explains the effect of temperature on the straightening of the

isolated fibres, but not suitable for the evaluation of latent pulp because it neglects the proportion of fibre flocs in the pulp sample by eliminating all the fibre flocs.

For the "Post" deflocculation conducted on the "Direct"ly treated samples, curl indices were high at all temperatures. This is because that a directly treated pulp sample was dominated by fibre flocs within it the fibres were highly deformed. Post-disintegration at 20℃ dispersed the flocs without changing their deformations, resulting in higher values of curl index. Since "Direct" treatment barely changed the structure of the fibre flocs at different temperatures, the curl indices of the fibres tied in the flocs were same after "Post" deflocculation treatment, with the value, at each temperature, being expected to be the value determined by "Direct" treatment plus certain constant value. This explains why the curve of "Direct"+"Post" shows the same trend as that of "Direct".

The above analysis reveals that the true value of curl index of a pulp sample can only be determined when every fibre in the sample is taken into account, and the appropriate way to determine the curl index of the sample containing flocs is to disperse the flocs by cold disintegration, rather than removing them from the pulp sample. As a result, the samples containing flocs, i.e. pulp samples treated for shorter than 5 minutes at all temperatures and the samples treated at 23°C at all sampling times in *Fig 6.1*, were post-disintegrated in a British Standard Disintegrator before the curl indices were measured. The results were then plotted in *Fig 6.5*, showing the effect of temperature on curl index in latency removal of TMP pulp. In comparison with the previous finding on fibre straightening of isolated fibres, the rate of fibre straightening at pulp suspension level is much slower since the process is limited by the time required to complete fibre deflocculation.

The effect of pulp consistency on curl index has been evaluated and presented in *Fig 6.6*. Within the range of consistency examined, consistency had no influence on curl index. As discussed previously, the change of fibre curl, when the pulp is completely deflocculated, is dependent on temperature only. The change of curl index will be influenced by consistency when the pulp is not completely dispersed, where the treatment at higher consistency will accelerates the process of fibre deflocculation, resulting in slightly lower curl index.

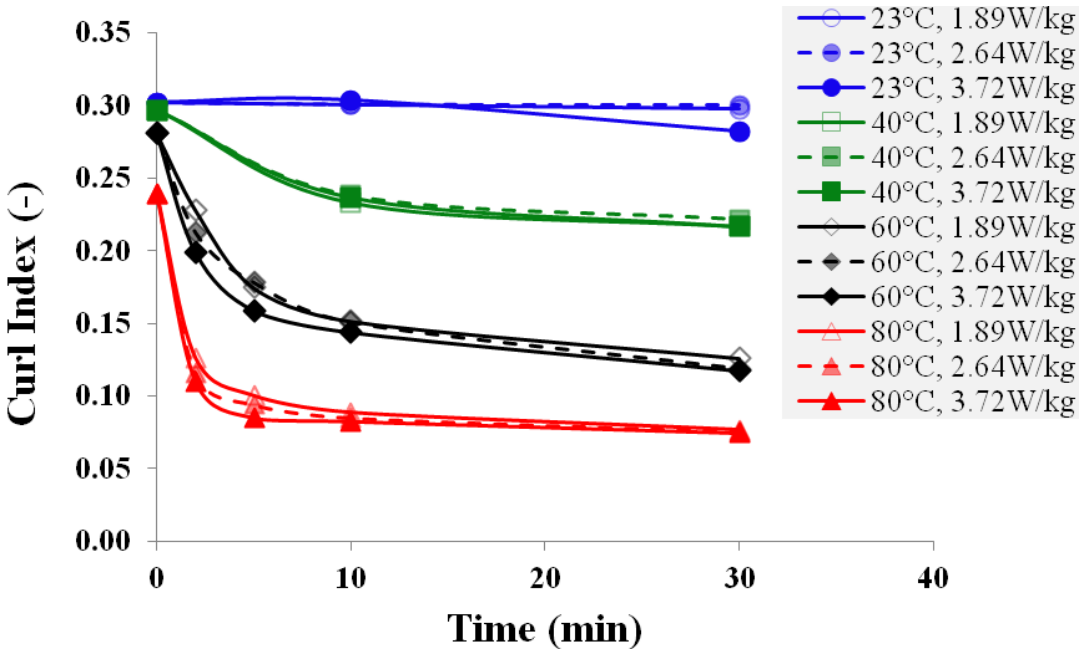

Fig 6.5 Effect of temperature on curl index. Reported values of curl index at all temperatures for treatment times of 0 and 2 minutes, and at 23°C for all treatment times were measured after the samples were post-disintegrated in a British Standard Disintegrator at a temperature of 20°C and a consistency of 0.3% for 5 minutes.

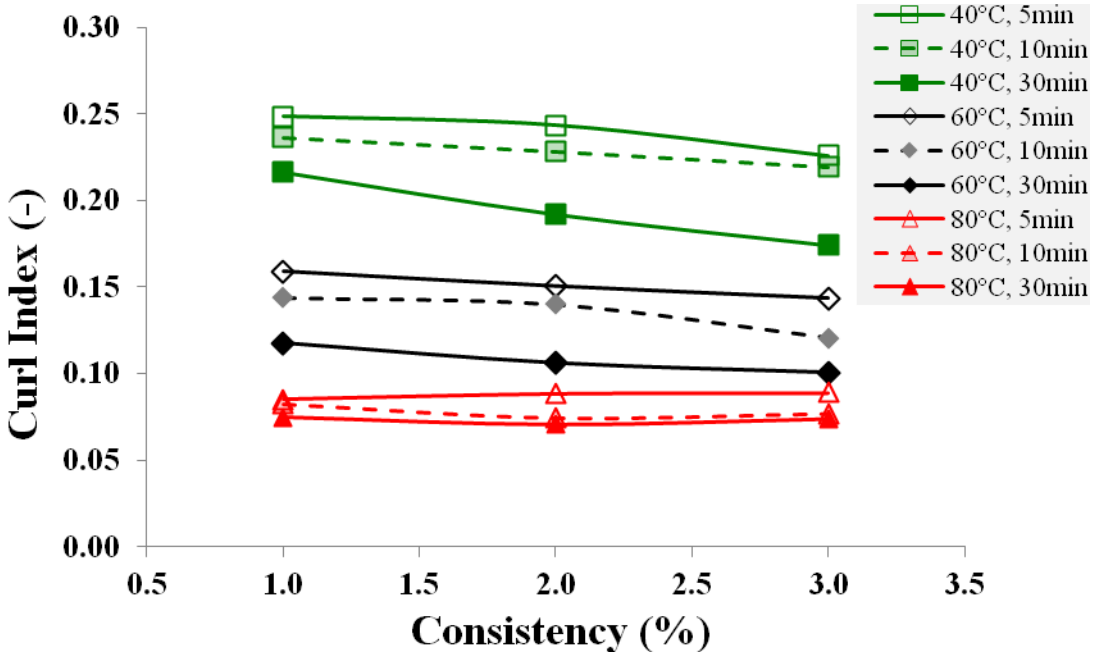

Fig 6.6 Effect of consistency on curl index. Experiments were carried out at a power intensity of 3.72 W/ kg-suspension.

6.2.2 Change in Dry-sheet Strength Properties

Handsheets were made for most of the treated pulp samples in the kinetic study as presented in Chapter 4 and the tensile and tear strengths were measured for each set of the handsheets. For those made from the pulp samples treated at same consistency but different power intensities, temperatures and times, substantial increase in both tensile and tear strengths have been found after latency was completely removed. As shown in *Figs 6.7* and *6.8*, a value of 8.7 Nm/g in tensile index and a value of 2.3 mNm²/g in tear index were obtained after latency was partially removed after the pulp sample was treated at a temperature of 40°C and a power intensity of 3.72 W/kg-suspension for 10 minutes. When latency was completely removed by treating the pulp sample at a temperature of 80°C and a power intensity of 3.72 W/kg-suspension for 30 minutes, the tensile and tear indices obtained were 29.6 Nm/g and 6.0 mNm²/g, respectively, an increase of over 160% for both properties. Although the increases in both tensile and tear strengths were much greater than those have been reported in the literature (Mohlin 1980a; Karnis 1993), attention should be paid to what caused the increase in tensile and tear strengths, rather than how much they increased.

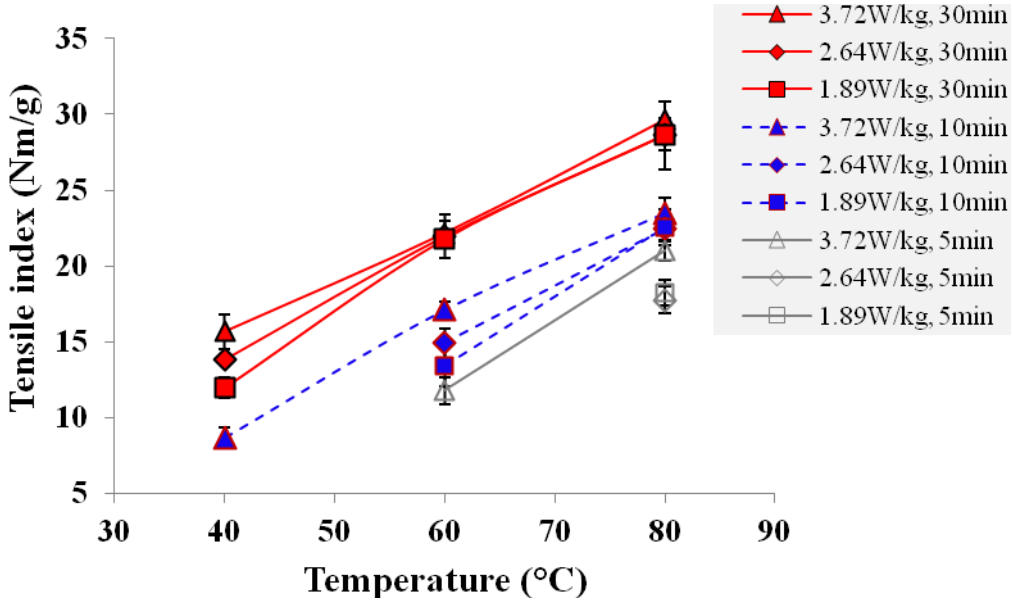

Fig 6.7 The change of tensile strength at different temperatures and power intensities. Experiments were carried out at a consistency of 1%. Standard deviations reported in the figure were automatically obtained in the measurement of the tensile strength for 10 or less tensile test specimens.

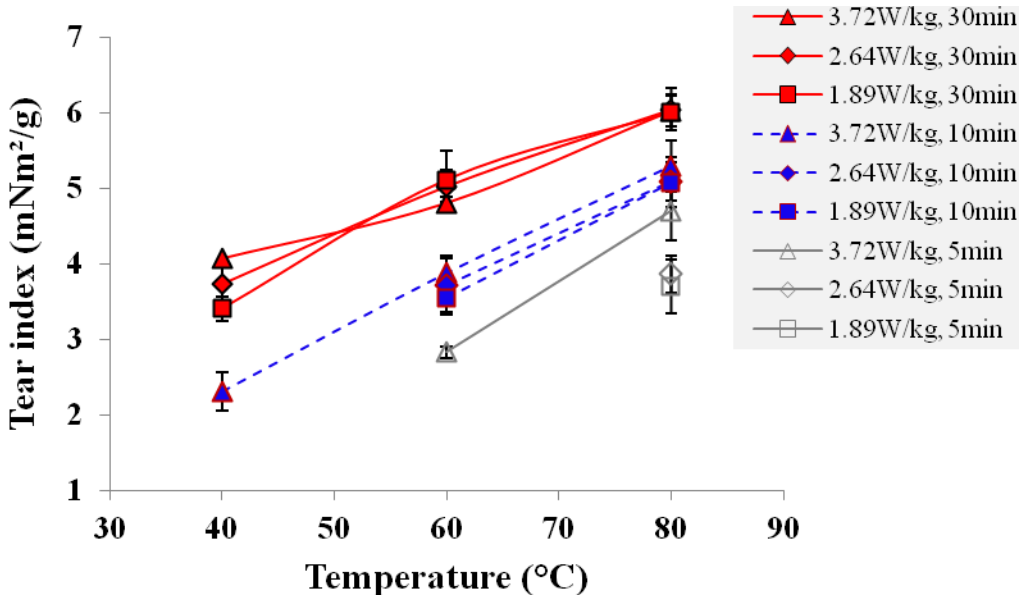

Fig 6.8 The change of tear strength at different temperatures and power intensities. Experiments were carried out at a consistency of 1%. Standard deviations reported in the figure were calculated from 4 tear indices measured for a set of tear test specimen.

The state of the treated pulp suspension can be characterized by the extent of fibre deflocculation and fibre straightening. The time required to obtain a complete deflocculation depends on the power intensity and temperature of the treatment. The higher the mixing speed is, the stronger the mechanical impact on fibre flocs is and the shorter the time is to break up all the flocs. At elevated temperatures, the fibres in the flocs are softened, making them easier to be separated.

The extent of fibre deflocculation is believed to account for the difference in strengths for the pulp samples treated at all same conditions but for different treatment times. For example, the main difference between the pulp samples treated for 5 and 30 minutes at same power intensity of 3.72 W/kg-suspension and same temperature of 60°C was that more flocs were left unbroken in the pulp sample after it was treated for 5 minutes, but the tensile strength obtained was only half of that of the pulp treated for 30 minutes. The loss in tensile strength is obviously due to poor sheet formation when there are more fibre flocs in the pulp sample, resulting in weak bonding between the flocs and their neighbor fibres, or less effective fibres involved in the fracture zone since certain amount of fibres are stuck in the flocs, or unevenly distribution of the stress during testing.

For the pulp samples that have been completely deflocculated after being treated for 30 minutes, the tensile index depends only on temperature. In comparison with complete straightening at high temperature, the treatment at low temperature straightened the fibres to a limited extent. For example, the difference in tensile strength between the pulp samples treated at 40 and 80°C was clearly attributed to the different extent of fibre straightening after the treatments. The mechanism of strength reduction by curled or kinked fibres has been explained as related to the reduced effective fibre length along which stress is transmitted in the sheet (Page 1969; Page *et al*. 1985), or uneven stress distribution in the network resulted from the readiness of the straight and deformed fibres to transmit load from one bond to another (Seth 2005; Seth 2006). In addition to these reasons, we also feel that the reduction in tensile strength may also results from a reduction in relative bonded area (RBA) resulted from high fibre curl. As shown in *Fig 6.9*, we find that tensile strength decrease with increased curl index. This is because that fibre curl, in absence of other effects, raises the bulk of the pulp sheet, resulting in a less closely formed fibre network with low RBA. The slight increase in fibre length (*Fig 6.10*) resulted from smoothing out dislocations and constrictions might be another factor that improves the tensile strength through improving the uniformity of load transfer (Cowan 1995).

For pulp samples that have been partially deflocculated, e.g. treatments for 10 minutes or less, the tensile index depends strongly on temperature but is affected by the power intensity of the treatment as well. The power intensity influences the tensile strength through changing the rate of fibre deflocculation. For equal length of time, the pulp treated at higher power intensity achieves higher extent of fibre deflocculation, resulting in higher value in tensile strength.

Similar to tensile strength, Elmendorf tear strength has been found strongly influenced by temperature and time of the treatment. Treatments at higher temperatures disperse the fibre flocs and straighten the fibres, resulting in better bonding and thus higher tear strength. At the same temperature, shorter time is insufficient to break up all the fibre flocs, which causes poor bonding and results in low tear strength. In addition to inter-fibre bonding, as previous discussed in Chapter 2, tear strength is influenced by fibre strength and fibre length. According to the experimental result, about 7% increase in fibre length has been found for

the sample treated at 80°C for 30 minutes comparing to the sample treated at 40°C for the same length of time. The increase in fibre length undoubtedly contributes to the improvement of tear strength, especially for weakly bonded sheet made from TMP pulp (Seth and Page 1988; Seth 1996).

It has been reported that individual fibre strength was much stronger than single bond strength (Davison 1972; Niskanen *et al*. 1999). In a tensile or tear strength test of TMP pulp handsheet, more fibres were pulled out rather than broken in the fracture zone. Thus, individual fibre strength was least considered in the interpretation of the experimental results here, even though it has been known as one of the most important factors that influence both tensile and tear strengths.

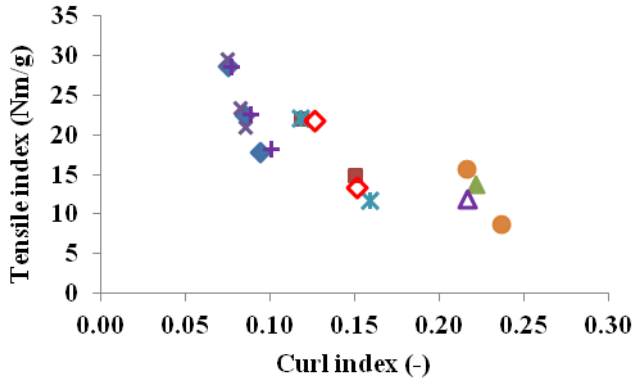

Fig 6.9 The change of tensile index as a function of curl index.

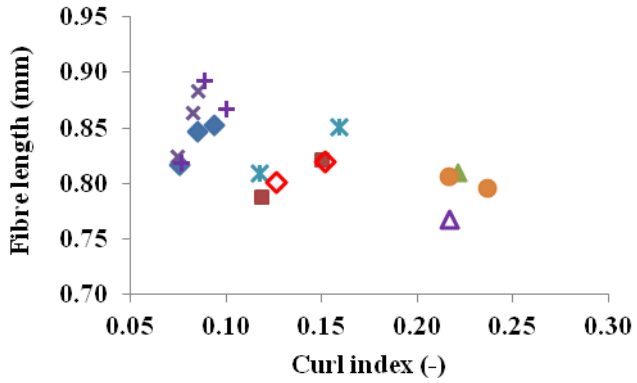

Fig 6.10 The change of fibre length as a function of curl index shows the slight increase in fibre length when the fibres become straightened.

The effect of consistency on tensile and tear strengths has been determined and shown in *Figs 6.11* and *6.12*. Within the range of consistency examined, consistency had no influence on tensile or tear strength for the pulp samples treated for 10 and 30 minutes at high temperatures of 60 and 80°C. For the pulp samples treated for shorter times or at lower temperatures, both tensile and tear strengths slightly increased with the increased consistency. At low consistency up to 4%, the change in consistency affects the operation of latency removal by changing the rate of fibre deflocculation for the treatments performed at same power intensity and temperature for same length of time, which is inferred from the change in freeness as a function of pulp consistency (*Fig 6.13*).

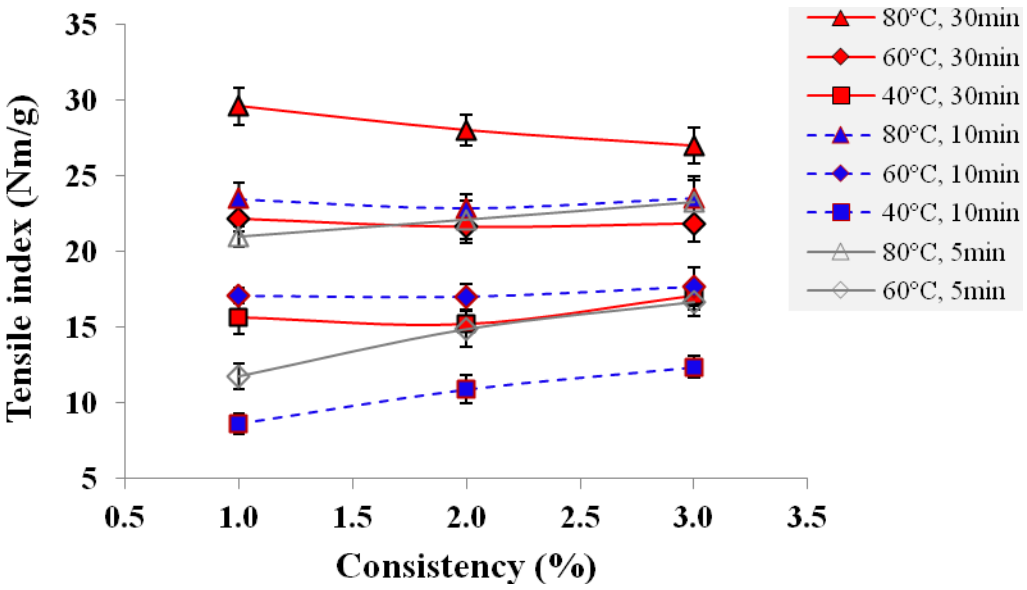

Fig 6.11 Effect of consistency on tensile strength. Experiments were carried out at a power intensity of 3.72 W/ kg-suspension.

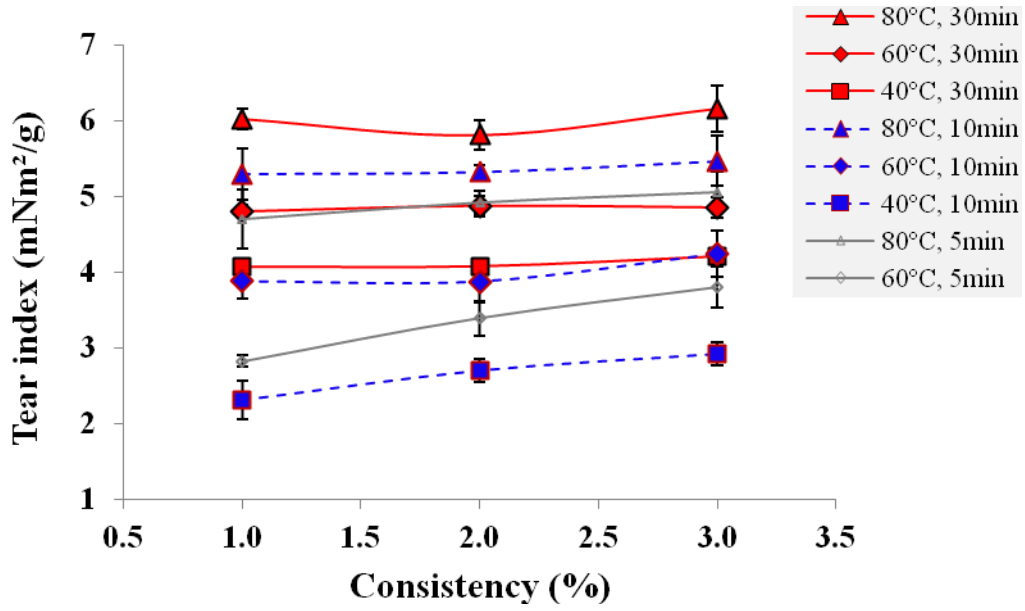

Fig 6.12 Effect of consistency on tear strength. Experiments were carried out at a power intensity of 3.72 W/ kg-suspension.

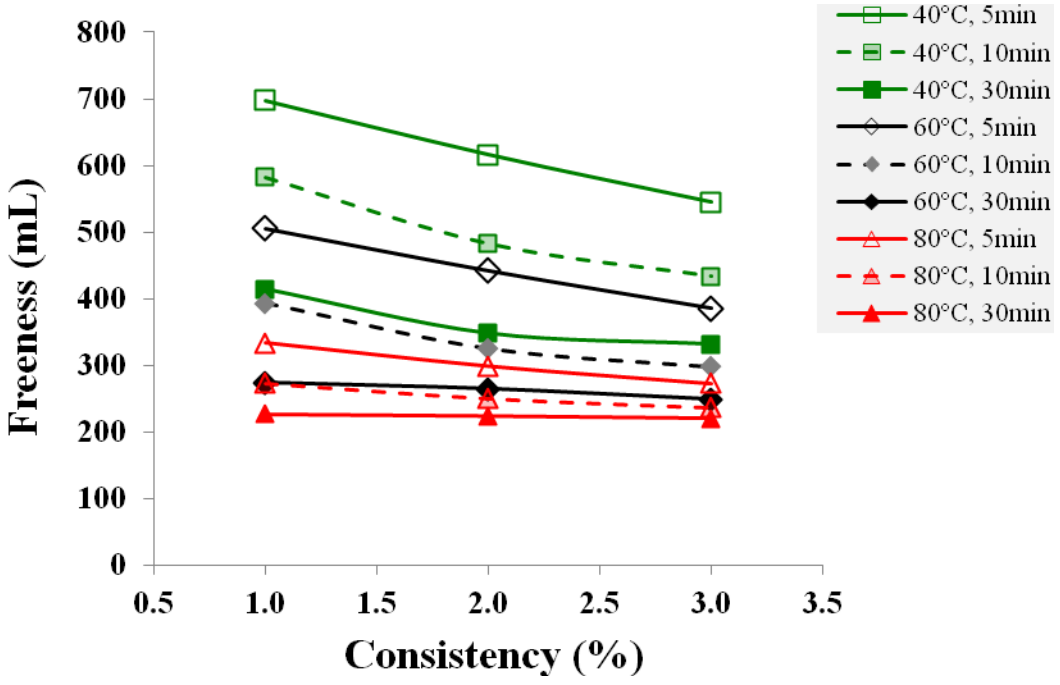

Fig 6.13 Effect of consistency on freeness. Experiments were carried out at a power intensity of 3.72 W/ kg-suspension.

6.2.3 The Relationships among Pulp Properties

As discussed in Chapter 2, fibre, pulp and dry sheet properties are connected to one another through fundamental properties such as fibre length, fibre curl or other forms of deformations, fibre strength, specific surface, bonded area, etc. In this section, effects has been made to establish the correlations between different properties.

For freeness and curl index, linear correlations has been found between freeness and curl index at each temperature examined in the study (*Fig 6.14*). The change of curl index is dependent on temperature but influenced by the extent of fibre deflocculation. While the change of freenss is influenced by both fibre curl and the extent of fibre deflocculation. When the pulp sample is disintegrated for longer time and achieved higher extent of fibre deflocculation, the effect of the existence of fibre flocs is minimzing. As a result, correlations between curl index and freeness are expected to be established at each temperature.

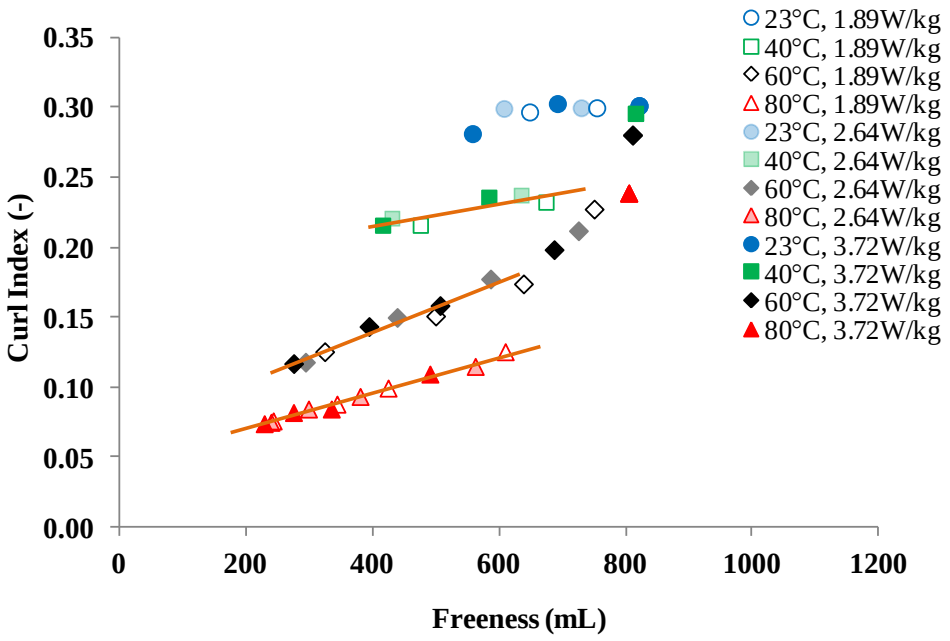

Fig 6.14 The relationship between freeness and curl index shows linear correlations at different temperatures. Experiments were carried out at a consistency of 1%. The curl indices presented in this figure are the same as that in *Fig 6.5*.

The correlations between property pairs such as freeness - tensile strength, freeness - tear strength, and tensile strength - tear strength are presented in *Figs 6.15 – 6.17*. In the treatment of a pulp sample, the curl index and the bulk continuously decreases as a result of fibre deflocculation and straightening, which leads to a more uniform pulp, an continuous decrease in freeness and increase in tensile and tear strengths. As seen in *Figs 6.1*5 and *6.16*, both tensile and tear strengths linearly increase till all latency is removed. A linear correlation has also been found between tensile and tear indices for the pulp samples treated at different temperatures, power intensities, consistencies and treatment times (*Fig 6.17*). The results presented here infer that tensile and tear strengths are developed through same mechanism as previously discussed, which influenced by the extent of fibre straightening and deflocculation in the operation of latency removal.

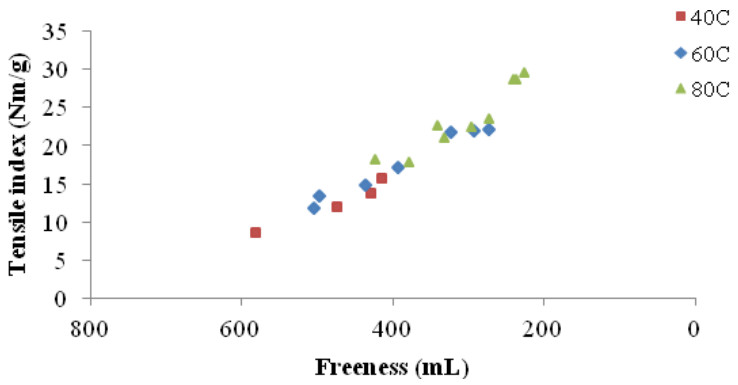

Fig 6.15 The change of tensile strength as a function of freeness. The data shown in the figure were from the pulp samples treated at a consistency of 1% but at different power intensities.

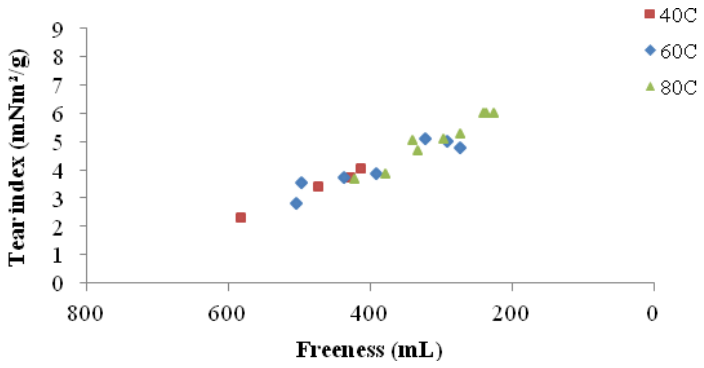

Fig 6.16 The change of tear strength as a function of freeness. The data shown in the figure were from the pulp samples treated at a consistency of 1% but at different power intensities.

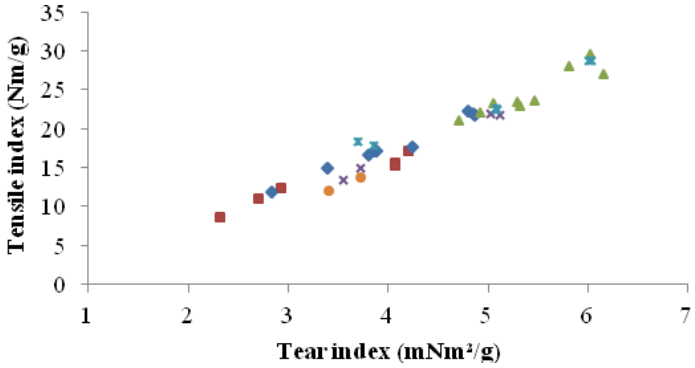

Fig 6.17 The plot of tensile index against tear index shows a linear correlation.

6.3 Discussion

6.3.1 The Existence of Fibre Flocs on the Measurement of Pulp Properties

In the operation of latency removal, both heat and mechanical action are indispensable, where the former is essential in straightening the fibres and the latter is vital in breaking up the fibre flocs and liberating all the fibres. The deflocculation process will be facilitated when the disintegration is carried out at elevated temperatures, but in nature it is the mechanical action that frees all the fibres from fibre flocs.

As discussed above, the existence of fibre flocs strongly influences the measurement of curl index and strength properties. The measurement of curl index performed by the FQA is on a large number of individual isolated fibres, which requires that the sample is fully deflocculated. When the measurement is carried out on the sample that contains fibre flocs, it is essential to have the pulp sample deflocculated to obtain the correct value of curl index. For the measurement of strength properties, the handsheets have to be formed before the measurements can be carried out. For the pulp samples that still have a large amount of fibre flocs after the treatment, forming handsheet is impossible, which results in the incompleteness of the experimental data.

The results presented in Chapter 3 reveals that fibre deflocculation is the rate controlling step, which requires much longer time to complete than fibre straightening. Despite the importance of fibre deflocculation in latency removal, the study on fibre deflocculation have

been found very limited in the literature in comparison with the comprehensive study on fibre straightening at either individual fibre level or pulp suspension level. There is no report in the literature on the rate of fibre deflocculation in the operation of latency removal nor any proposed pulp or fibre properties to characterize this process. In this study, it has been found that fibre deflocculation at low temperature can be characterized by freeness.

6.3.2 Characterization of Fibre Deflocculation by Freeness

In mechanical treatment of a TMP pulp, the fibre flocs in the pulp sample break up continuously, resulting in the progressive decrease in freeness. When the treatment is carried out at room temperature, the primary change of the pulp sample is the continuous disruption of the fibre flocs, until all the fibres were free from the flocs. Being influenced primarily by the fibre specific surface (Forgacs 1963) and fines content (Clark 1970; Mohlin 1980b; Biermann 1996), freeness has been found, as presented in Chapter 4, working well in characterizing latency removal, regardless whether the suspension has been fully deflocculated or not. The change in freeness at different mechanical energy levels was explored using our laboratory experimental setup (the vertical mixer) as describe in Chapter 4 for the TMP pulp suspension at 1 and 3%, respectively, and the result was compared with treatments carried out using a British Standard Disintegrator (BSD).

As shown in *Fig 6.18*, freeness changes as a function of treatment energy for both 1 and 3% consistencies and it is not dependant on the type of the mixing device, as long as the treatment is carried out where turbulent mixing is provided. Real images added for selected points (a) – (b) for 1% consistency and (c) – (e) for 3% consistency show clearly the process of fibre deflocculation, displayed as the diminishing of fibre flocs which are represented by the dark area in each image. At constant treatment energy, fibre deflocculation process is facilitated at higher consistency, where the fibres and flocs exert mechanical forces to their neighbor fibres and flocs more effectively than at low consistency, resulting in a greater extent of fibre deflocculation and thus much lower values in freeness.

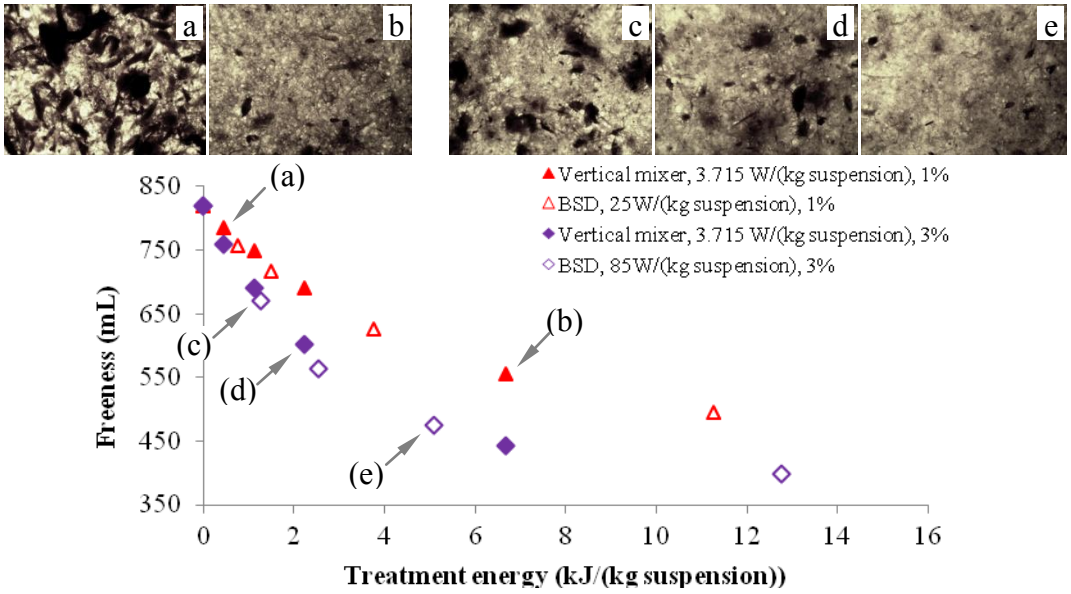

Fig 6.18 Characterization of fibre deflocculation by the change of freeness as a function of treatment energy. The treatments were carried out at a temperature of 23°C but at consistencies of 1 and 3% using the vertical mixer and British Standard Disintegrator. Images presented on top of the figure were taken using an optical microscope on the handsheet made using the treated pulp samples at selected points (a) – (e) in the figure.

Although the characterization is limited by the treatment conditions, especially temperature, it reveals the relationship between freeness and fibre deflocculation. At a higher temperature, the treatment will result in certain extent of fibre straightening and improved fibre deflocculation as a result of fibre softening, both of which will influence the characterization of fibre deflocculation. When re-examining the process of latency removal, it is clear that complete latency removal is obtained when the pulp is completely deflocculated and the fibres in the pulp are completely straightened. Any treatment results in the change of the original state of the pulp sample but without achieving complete fibre deflocculation and fibre straightening can be defined as partial latency removal. Partial latency removal can be resulted from complete fibre deflocculation but incomplete fibre straightening, e.g. cold disintegration, or incomplete fibre deflocculation and incomplete fibre straightening, e.g. insufficient disintegration at certain temperature. The importance of fibre deflocculation suggests that a more accurate mechanism of latency removal shall include the description of fibre deflocculation, as latency removal is resulted from the combination of external mechanical forces and internal elastic force from the cellulose, which are acting on the fibres

and fibre flocs.

6.4 Conclusions

Latency removal recovers the originally-possessed but unintentionally-sequestered pulp properties. Both fibre curl and strength properties are influenced by the existence of fibre flocs when the pulp suspension is not fully dispersed. When deflocculated, fibre curl depends solely on temperature at which the pulp suspension is treated. Both tensile and tear strengths are gradually developed as latency is released and the retrieve of these properties is influenced by the extent of fibre deflocculation and fibre straightening. The role of mechanical action is to disperse the highly deflocculated pulp. For a fixed time of treatment, higher power intensity leads to higher tensile and tear strengths as a result of increased rate of fibre deflocculation. Higher consistencies facilitate the development of tensile and tear strengths by speeding up the rate of fibre deflocculation. Within the conditions examined, linear correlations exist between freeness and curl index, strength properties and freeness, and between tensile and tear indices. Overall, fibre deflocculation is the bottleneck and improved fibre deflocculation process is the solution to achieve energy reduction in the operation of latency removal.

Chapter 7: Latency Removal of Primary BCTMP Pulp

All the studies on latency removal in the literature have been conducted on secondary refiner pulp. Yet the recent development on low consistency refining brought up a new topic - latency removal of primary mechanical pulp. Being a part of Quesnel River Pulp (QRP)'s low consistency refining renovation project, a study was conducted to investigate the feasibility of using a downsized chest as a potential latency chest for the new pulping process.

As shown in *Fig 7.1*, the mill's current BCTMP process starts with chemical pre-treatment of the wood chips. The pre-treated chips are refined at primary refining stage and followed by an inter-stage washing and dewatering stage. The pulp is then fed into the secondary refiner after which it is treated in the latency chest. The renovation plan is to replace the secondary refiner with one or more low consistency refiners, and move the latency removal process to intermediately after the primary refining stage, where the operation of latency removal of primary BCTMP pulp is carried out in a downsized latency chest, e.g. the unrefined reject chest. The examination of the mill's process reveals that the current inter-stage washing chest (the dilution chest), where the treatment is essentially an operation of latency removal of primary BCTMP pulp, has the potential to be utilized as a latency chest, and the investigation in this chapter has been carried out on the inter-stage washing chest. The proposed process flow diagram is presented in *Fig 7.2*. The investigation is to examine the effectiveness of latency removal of primary refiner BCTMP pulp using the mill's current inter-stage washing chest by comparing the laboratory experimental result on latency removal and the on-site latency removal in the inter-stage washing chest.

7.1 Materials and Methods

High consistency (45%) SPF (spruce (75%), pine (20%) and fir (5%)) primary BCTMP pulp obtained from QRP was used in this study. The study was conducted using our laboratory experimental setup as described in Chapter 4. The study characterizes the effect of temperature and power intensity on latency removal, and evaluates the feasibility of latency removal using current inter-stage washing chest. Two main pulp properties, i.e. freeness and curl index, have been examined.

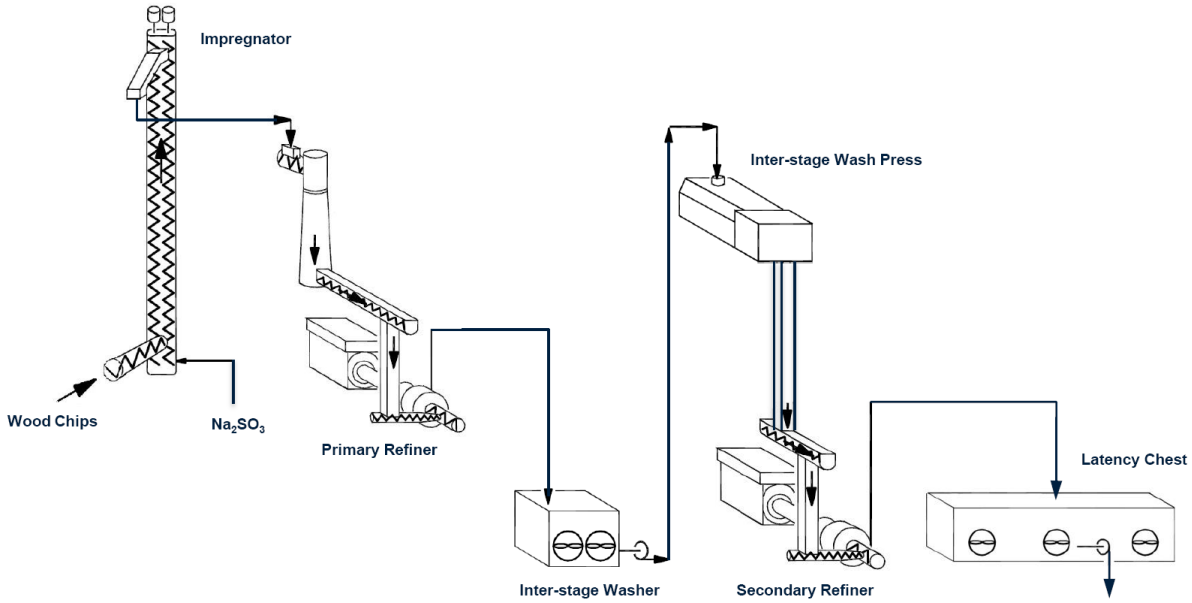

Fig 7.1 The flow diagram of the mill's current BCTMP process. The diagram is simplified from the mill's overall BCTMP process flow diagram.

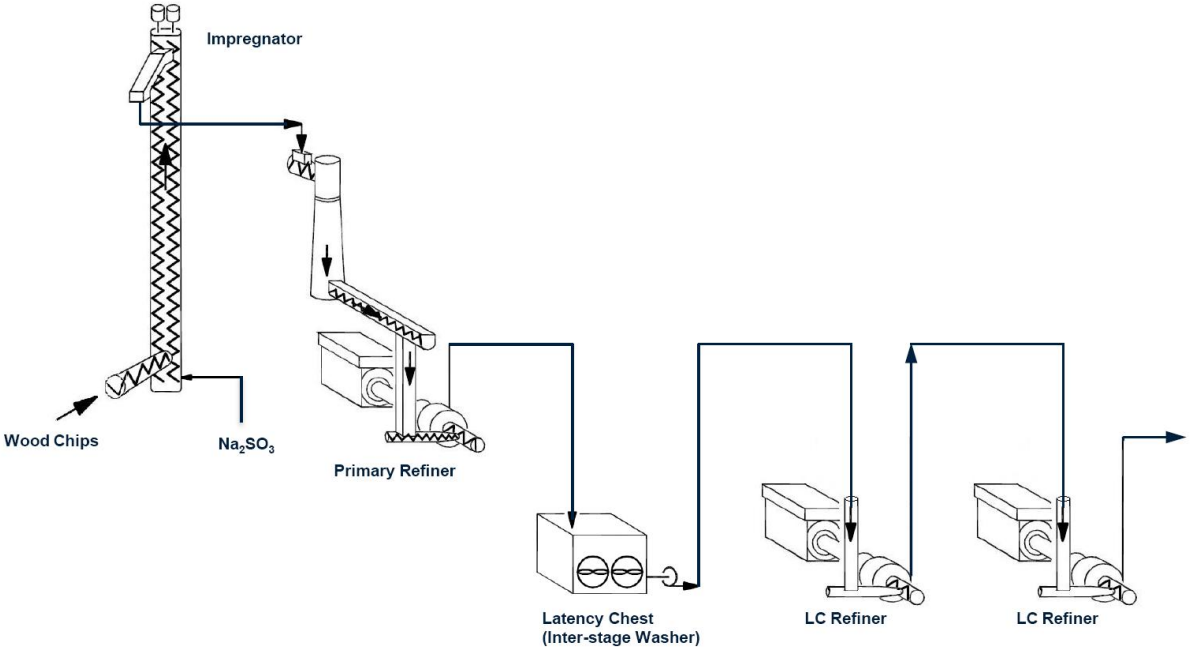

Fig 7.2 The flow diagram of the proposed BCTMP process.

7.2 Results

The study started with the experiment on the effect of temperature on latency removal of primary BCTMP pulp, characterized by freeness and curl index through cold and hot treatments. As shown in *Figs 7.3* and *7.4*, either freeness or curl index was continuously

decreased until approaching asymptotically to a “floor level” value, which was dependent on the curliness of the fibres controlled by the temperature at which the treatment was carried out. Prolonged time was required to get the pulp suspension fully dispersed for the treatment at room temperature in comparison with the hot treatment at 83°C, where 2 minutes was sufficient to remove almost all the latency at a power intensity of 3.72 W/kg-suspension.

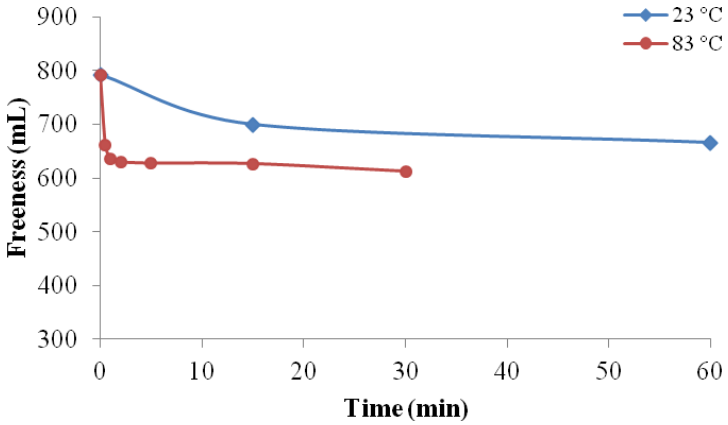

Fig 7.3 Change of freeness in latency removal. Experiments were carried out at a consistency of 3% and a power intensity of 3.72 W/ kg- suspension. Freeness at time zero was measured directly on the original pulp sample without any treatment.

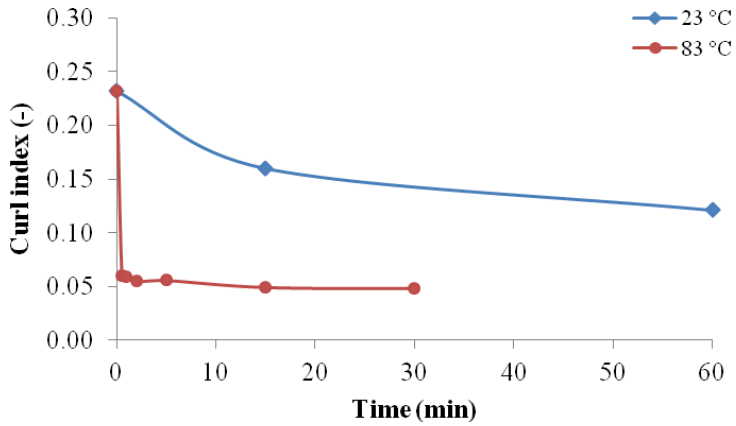

Fig 7.4 Change of curl index in latency removal. Experiments were carried out at a consistency of 3% and a power intensity of 3.72 W/ kg-suspension. Curl index at time zero was measured after the pulp suspension was disintegrated at a consistency of 0.3% and a temperature of 20°C in a British Standard Disintegrator for 5 minutes.

The study then moved to examine the effect of power intensity on latency removal through applying same power intensity as that is applied in the inter-stage washing chest in QRP. Unfortunately, the lab set-up has been designed for batch reaction and is unable to simulate the continuous operation of the inter-stage washing. Experiments were carried at same temperature and power intensity as applied in QRP, but at a lower consistency of 2% to achieve complete mixing. In comparison with the hot treatment at a power intensity of 3.72 W/kg-suspension, lower energy slightly lowers the rate of dropping in freeness, but 5 minutes is sufficient to remove all the latency (*Fig 7.5*). The change of curl index (*Fig 7.6*) is identical for different power intensities/energies applied, which supports the previous finding that curl index depends solely on temperature at which the treatment is carried out, and not dependent on the consistency or power intensity.

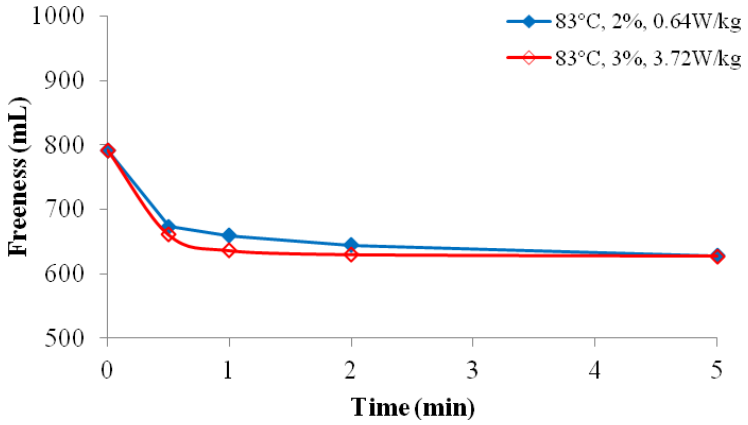

Fig 7.5 Effect of power intensity on latency removal of primary BCTMP pulp, characterized by freeness.

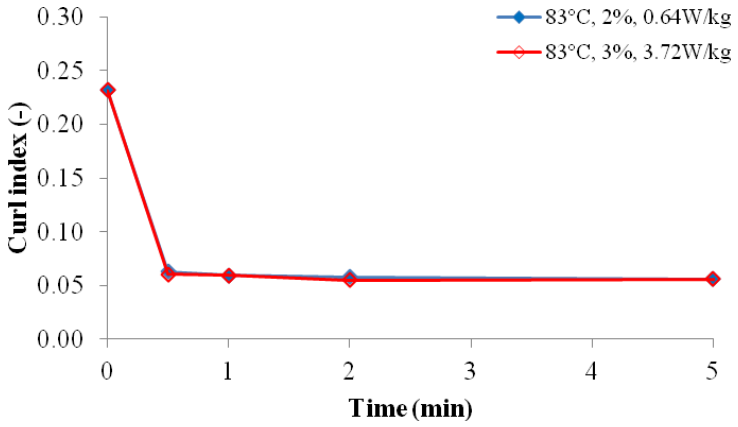

Fig 7.6 Effect of power intensity on latency removal of primary BCTMP pulp characterized by curl index shows that the change in curl index depends solely on temperature.

The laboratory result was than compared with the test result on the inter-stage washing outlet sample, to determine the quality of latency removal by inter-stage washing operation. Rather than achieving complete motion, inter-stage washing chest is operated in a zone-agitation mode. As a result, good mixing in the agitation zone and poor mixing outside the mixing zone exist simultaneously. The existence of non-ideal mixing (bypassing, dead zone, etc) lowers the quality of latency removal, achieving only partial latency removal. As shown in *Fig 7.7*, the freeness of the inter-stage washing chest outlet sample is higher than that of the sample treated in the laboratory at same energy level, indicating some remaining latency after inter-stage washing process. Both laboratory and mill measurement on freeness and curl index were carried out on inter-stage washing chest outlet sample. For curl index, the on-site measurement with the hot sample directly collected from the chest gives a better result in latency removal (*Fig 7.8*). The inevitable cooling of the sample before it was sent to the laboratory is believed to be the cause of the difference between the laboratory and mill measurement, resulting in a return of a small portion of latency for the pulp sample tested in the laboratory.

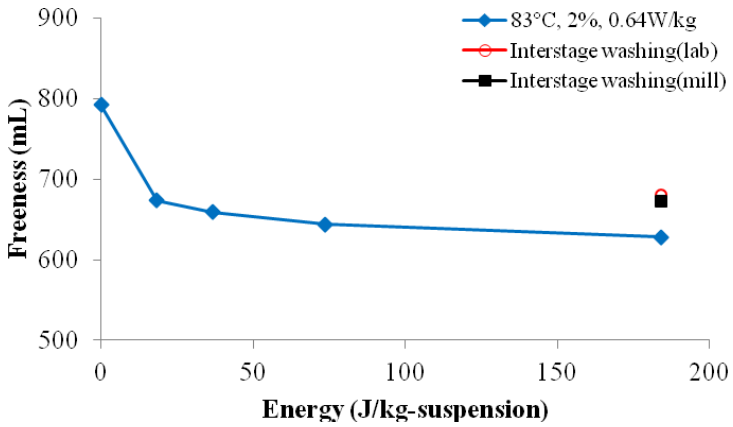

Fig 7.7 Effect of treatment energy on latency removal characterized by freeness shows that inter-stage washing process removes the majority of the latency.

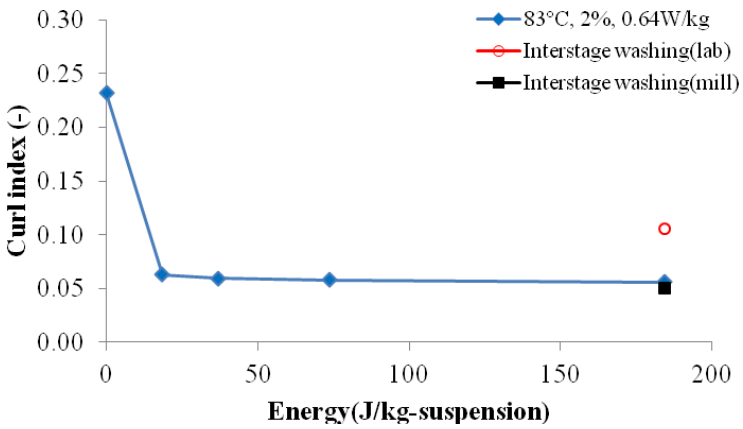

Fig 7.8 Effect of treatment energy on latency removal characterized by curl index reveals a small amount of latency return.

7.3 Conclusions

Complete latency removal of primary BCTMP pulp, under complete mixing, is able to be achieved in 5 minutes at a power intensity of 0.64 W/ kg-suspension, the same power intensity applied in the mill's inter-stage washing chest. The inter-stage washing process removes a large portion of the latency and complete latency removal can be achieved through better mixing in the chest.

Chapter 8: Conclusions and Future Work

8.1 Conclusions

This study was set out to determine the kinetic model of latency removal which can be used to optimize latency removal process in pulp mills and seek the potential of energy reduction in the operation of latency removal. Efforts have been made to find the answers to a number of key questions in this study including 1) What are the roles of fibre straightening and fibre deflocculation in latency removal? 2) What is the kinetics available to model latency removal as a function of key variables? 3) How to characterize latency removal by a number of different pulp properties?

In latency removal of (chemi)thermomechanical pulp, there are two tasks to be accomplished - fibre deflocculation and fibre straightening, and latency is essentially removed when the fibres are liberated from the fibre flocs and straightened. The study conducted on the straightening of isolated never-dried high consistency mechanical pulp fibres undergoing heat and moisture treatments shows that maximum fibre straightening can be achieved as short as one second. Fibres deflect under during the uptake of room-temperature water, but the extent of straightening is limited and the fibres return to their original curliness to various magnitudes after removal of the water. Being treated with hot water at a temperature near the glass transition point of lignin, the fibres achieve their maximum straightening after approximately one second and the straightening is permanent. Latency removal of isolated fibres is resulted from lignin softening at elevated temperatures during which the internal stresses developed are released and the elastically restrained celluloses restore the fibres to their original straightness. Fibre deflocculation is the rate controlling step in latency removal, which requires much longer time than fibre straightening. The rate of fibre deflocculation is dependents on the power intensity applied and is influenced by temperature of the treatment and pulp consistency. The remaining fibre flocs resulted from incomplete fibre deflocculation has strong influence on the measurement on fibre curl and on dry sheet strength properties.

The characterization of latency removal by freeness shows that for either TMP or BCTMP pulp, the release of latency proceeds rapidly in the initial phase followed by the second phase, in which the freeness releasing rate is much slower and approaches asymptotically to a

"floor level". The kinetics of latency removal of secondary refiner TMP and BCTMP pulps follow a one-and-a-half order and a second order, respectively, involving disintegration temperature, pulp consistency and power intensity of the treatment. The kinetic models developed accurately predict the change in freeness at different treatment conditions and the analysis of the models show that latency removal is favored by high temperature, high power intensity and high consistency up to 5%.

When deflocculated, fibre curl depends solely on temperature at which the pulp suspension is treated. For a fixed time of treatment, higher power intensity leads to lower freeness and higher tensile and tear strengths as a result of increased rate of fibre deflocculation. Higher consistencies facilitate the development of tensile and tear strengths by speeding up the rate of fibre deflocculation. Within the conditions examined, linear correlations exist between freeness and curl index, strength properties and freeness, and between tensile and tear indices.

Overall, freeness is easy to measure and is the only property that works reliably in the entire domain; however, it is not a conserved property. Curl measurement is limit by the sample conditions, especially for those treated at low temperatures where complete deflocculation is not achieved; however, it is a conserved property. Fibre deflocculation is the bottleneck in the operation of latency removal. There is potential to optimize current operation of latency removal in the pulp mills and energy reduction can be achieved by applying higher power intensity.

8.2 Contribution to Knowledge

1. Study on fibre straightening and the determination of the rate of fibre straightening provides fundamental knowledge to the operation of latency removal and reveals that the improvement in fibre deflocculation is the solution to the optimization of latency removal process.
2. Kinetic models were developed for TMP and BCTMP pulps, both of which were expressed as that the rate of latency removal is a function of the freeness involving disintegration temperature, power intensity of the treatment and pulp consistency.

These original models are available to be used as a tool in predicting the change of freeness in latency removal.

3. Linear correlations were established between property pairs such as freeness – curl index, freeness – tensile index, freeness – tear index and tensile index – tear index, which provides a data network in characterizing latency removal by different pulp properties.
4. The potential of energy reduction was found as increasing the power intensity of latency removal process, which will lower the energy consumed to remove all the latency, and shorten the time required to do it which leads to the increase in production rate.

8.3 Limitation of the Study

The study was conducted using a batch "reactor" rather than a CSTR. As a consequence of this methodology, the direct comparison between the laboratory results and industrial data is not appropriate. In order to determine the pure kinetics of latency removal, all the laboratory experiments were conducted under a turbulent mixing condition, which is different from the zone mixing mode operated in the latency chest in the pulp mills. As a result, the model can only be used to simulate the mixing in the perfect mixed zone in the latency chest.

8.4 Recommendations for Future Work

1. Design and use a CSTR system to examine latency removal and develop a new model to simulate latency removal operated in a latency chest.
2. Study latency removal of primary refiner pulp in combination with low consistency refining system to optimize the energy consumption in such a combined system.
3. Optimize latency removal through improved mechanical design.

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Appendices

Appendix A

Data Analysis for the Development of Kinetic Model

Data available in the literature for the development of kinetic expression are presented here. The data is used to determine the kinetic order or the disintegration process, the relationship between the normalized freeness and different parameters, i.e. disintegration temperature, pulp consistency and energy intensity, from which the overall kinetic expression could be derived.

Table A.1 Differential analysis of the data in the literature for determining kinetic order (Beath *et al*., 1966; Dawson *et al*., 1978)

	Temperature ℃	Time min	Freeness ml	F_0	F_f	$\frac{F-F_f}{F_0-F_f}$	$-\frac{dF}{dt}$	$\ln\left(\frac{F-F_f}{F_0-F_f}\right)$	$\ln\left(-\frac{dF}{dt}\right)$
Dawson *et al*.; BSD – Hot Disintegration	85	0	399.66	399.66	175.16	1	38.742	0	3.657
Dawson *et al*.; BSD – Hot Disintegration	85	5	265.83	399.66	175.16	0.404	16.243	-0.906	2.788
Dawson *et al*.; BSD – Hot Disintegration	85	10	219.04	399.66	175.16	0.195	6.810	-1.635	1.918
Dawson *et al*.; BSD – Hot Disintegration	85	15	193.55	399.66	175.16	0.082	2.855	-2.501	1.049
Dawson *et al*.; BSD – Hot Disintegration	85	30	175.16	399.66	175.16	0	0.210	N/A	-1.558
The exponential relation between F and t is obtained as $F = 222.8519 \times e^{\left(\frac{-t}{5.7522}\right)} + 176.0284$									
Dawson *et al*.; Recirculation - RR = 1 min $^{-1}$	86	0	477.25	477.25	240.47	1	116.106	0	4.755
Dawson *et al*.; Recirculation - RR = 1 min $^{-1}$	86	1	449.94	477.25	240.47	0.886	74.099	-0.121	4.305
Dawson *et al*.; Recirculation - RR = 1 min $^{-1}$	86	2	308.92	477.25	240.47	0.289	47.291	-1.240	3.856
Dawson *et al*.; Recirculation - RR = 1 min $^{-1}$	86	4	269.74	477.25	240.47	0.124	19.262	-2.090	2.958
Dawson *et al*.; Recirculation - RR = 1 min $^{-1}$	86	10	242.70	477.25	240.47	0.009	1.302	-4.667	0.264
Dawson *et al*.; Recirculation - RR = 1 min $^{-1}$	86	15	240.47	477.25	240.47	0	0.138	N/A	-1.982
The exponential relation between F and t is obtained as $F = 258.5326 \times e^{\left(\frac{-t}{2.2267}\right)} + 235.2865$									

Beath *et al.*; BSD - Hot Disintegration	85	0	223.3	223.3	119.5	1	59.270	0	4.082
Beath *et al.*; BSD - Hot Disintegration	85	3	138.6	223.3	119.5	0.184	10.674	-1.392	2.368
Beath *et al.*; BSD - Hot Disintegration	85	5	124.9	223.3	119.5	0.052	3.404	-2.250	1.225
Beath *et al.*; BSD - Hot Disintegration	85	10	120.4	223.3	119.5	0.009	0.195	-2.802	-1.632
Beath *et al.*; BSD - Hot Disintegration	85	20	119.5	223.3	119.5	0	0.001	N/A	-7.347

The exponential relation between F and t is obtained as $F = 103.7218 \times e^{\left(\frac{-t}{1.74998}\right)} + 119.5998$

Table A.2 Integral analysis of the data in the literature for determining kinetic order (Beath *et al.*, 1966; Dawson *et al.*, 1978)

Dawson *et al.*, 1978 – BSD – Hot Disintegration

$\left(\frac{F-F_f}{F_0-F_f}\right)^{0.5} = -0.0336t + 0.8854$, R^2=0.8711 @n=0.5

$\left(\frac{F-F_f}{F_0-F_f}\right)^{0.2} = -0.019t + 0.9567$, R^2=0.9343 @n=0.8

$\ln\left(\frac{F-F_f}{F_0-F_f}\right) = -0.1225t + 0.1887$, R^2=0.9666 @n=1

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.2} = 0.0322t + 1.0269$, R^2=0.9883 @n=1.2

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.5} = 0.1256t + 0.983$, R^2=0.9994 @n=1.5

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.7} = 0.242t + 0.8289$, R^2=0.9942 @n=1.7

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-1} = 0.5747t + 0.1718$, R^2=0.9737 @n=2

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-1.5} = 2.1533t - 4.0592$, R^2=0.9255 @n=2.5

Dawson *et al*., 1978 - Recirculation - RR = 1 min $^{-1}$

$\left(\frac{F-F_f}{F_0-F_f}\right)^{0.5} = -0.0832t + 0.8684$, R^2=0.7916 @n=0.5

$\left(\frac{F-F_f}{F_0-F_f}\right)^{0.2} = -0.0596t + 0.9745$, R^2=0.9283 @n=0.8

$\ln\left(\frac{F-F_f}{F_0-F_f}\right) = -0.4741t + 0.1233$, R^2=0.9812 @n=1

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.2} = 0.1604t + 0.8665$, R^2=0.9963 @n=1.2

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.4} = 0.5746t + 0.2687$, R^2=0.9859 @n=1.4

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.7} = 2.6418t - 3.5067$, R^2=0.9553 @n=1.7

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-1} = 10.812t - 19.965$, R^2=0.9298 @n=2

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-1.5} = 106.86t - 222.81$, R^2=0.9082 @n=2.5

Beath *et al*., 1966

$\left(\frac{F-F_f}{F_0-F_f}\right)^{0.5} = -0.0844t + 0.8183$, R^2=0.7928 @n=0.5

$\ln\left(\frac{F-F_f}{F_0-F_f}\right) = -0.477t - 0.2418$, R^2=0.9784 @n=1

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.2} = 0.1640t + 0.9775$, R^2=0.9965 @n=1.2

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.3} = 0.3310t + 0.8599$, R^2=0.9906 @n=1.3

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-0.4} = 0.6034t + 0.5897$, R^2=0.9777 @n=1.4

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-1} = 12.895t - 19.949$, R^2=0.8673 @n=2

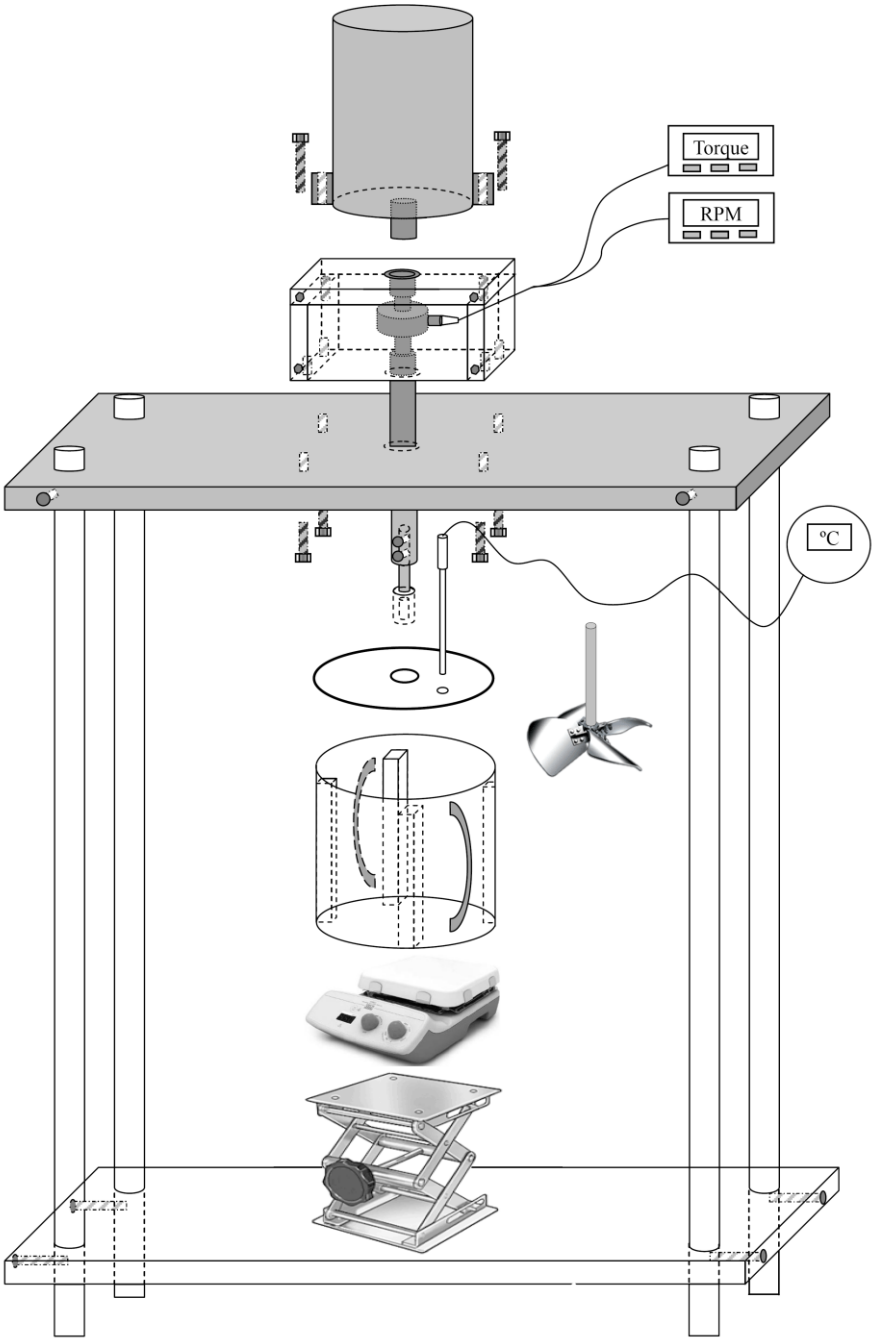
$\left(\frac{F-F_f}{F_0-F_f}\right)^{-1.5} = 145.16t - 275.43$, R^2=0.8145 @n=2.5

$\left(\frac{F-F_f}{F_0-F_f}\right)^{-4} = 331.24t - 580.95$, R^2=0.88 @n=5

Appendix B

The experimental setup and experimental data obtained for the kinetic model of latency removal of TMP pulp are presented here.

B.1 Schematic of Experimental Setup for Latency Removal Kinetics



B.2 Experimental Data on Latency Removal of Secondary TMP Pulp

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm²/g	stiffness, MNm/kg	bulk, cm³/g
30	1	40	1.89	**473.86**	0.768	1.405	2.053	**0.2165**	0.2145	2.525	0.23152	1.3624	61.3071	0.227	264.80	**11.95**	1.7	1.218	308.70	**3.40**	1.347	3.78
				473.03								1.3565				**0.693**	0.14	0.071	303.8	**0.16**	0.1132	
				474.99								1.3621							323.4			
				473.55								1.3628							303.8			
				1.02								1.3652							303.8			
												1.3653										
30	1	60	1.89	**322.54**	0.802	1.462	2.1085	**0.126**	0.1205	1.79	0.19976	1.3595	61.1757	0.196	306.25	**21.77**	1.79	2.219	455.70	**5.11**	2.403	3.27
				321.71								1.3508				**0.542**	0.1	0.055	431.2	**0.38**	0.07776	
				323.25								1.3552							441.0			
				322.67								1.3615							480.2			
				0.78								1.3643							470.4			
												1.3655										
30	1	80	1.89	**241.08**	0.819	1.499	2.161	**0.0765**	0.0715	1.075	0.19656	1.3555	60.9984	0.193	310.33	**28.64**	1.72	2.920	509.60	**6.00**	3.267	3.22
				241.85								1.3488				**2.249**	0.13	0.229	499.8	**0.23**	0.2215	
				241.00								1.3503							499.8			
				240.40								1.3562							509.6			
				0.73								1.3598							529.2			
												1.3625										
10	1	40	1.89	**672.62**	0.755	1.392	2.039	**0.233**	0.2425	2.59												
				669.96																		
				673.64																		
				674.26																		

				2.32																		
10	1	60	1.89	**498.08**	0.820	1.523	2.209	**0.1515**	0.1415	1.975	0.21676	1.3511	60.8013	0.214	280.50	**13.37**	1.61	1.363	215.60	**3.55**	1.605	3.57
				497.75								1.3418				**1.336**	0.13	0.136	215.6	**0.23**	0.1614	
				497.70								1.3438							205.8			
				498.80								1.3552							205.8			
				0.62								1.3573							235.2			
												1.3576										
10	1	80	1.89	**341.96**	0.893	1.633	2.3075	**0.0885**	0.083	1.225	0.20396	1.3619	61.2855	0.200	300.48	**22.57**	1.52	2.301	311.15	**5.08**	2.747	3.33
				345.54								1.3504				**1.167**	0.15	0.119	294.0	**0.33**	0.08675	
				340.09								1.3622							333.2			
				340.25								1.3635							294.0			
				3.10								1.3659							323.4			
												1.3675										
5	1	40	1.89	**742.87**	0.842	1.509	2.135	**0.2265**	0.236	2.43												
				743.65																		
				742.05																		
				742.90																		
				0.80																		
5	1	60	1.89	**637.02**	0.850	1.557	2.234	**0.1745**	0.1705	2.115												
				635.70																		
				638.75																		
				636.60																		
				1.57																		
5	1	80	1.89	**422.86**	0.867	1.598	2.275	**0.1**	0.092	1.34	0.20696	1.3386	60.2361	0.206	291.05	**18.24**	1.41	1.859	222.85	**3.70**	2.377	3.44
				423.70								1.3308				**0.856**	0.1	0.087	235.2	**0.36**	0.07819	

				426.69								1.3362							245.0			
				418.18								1.3416							215.2			
				4.32								1.3420							196.0			
												1.3423										
2	1	60	1.89	**748.86**	0.878	1.594	2.2555	**0.169**	0.1685	2.03												
				751.48																		
				747.39																		
				747.70																		
				2.28																		
2	1	80	1.89	**608.16**	0.906	1.643	2.322	**0.11**	0.1035	1.405												
				607.70																		
				611.38																		
				605.40																		
				3.02																		
10	1	23	1.89	**752.95**	0.8395	1.499	2.121	**0.3005**	0.316	2.875												
				752.70																		
				752.75																		
				753.40																		
				0.39																		
30	1	23	1.89	**646.76**	0.851	1.5115	2.126	**0.2975**	0.3065	2.820												
				645.85																		
				648.12																		
				646.30																		
				1.20																		

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm ²/g	stiffness, MNm/kg	bulk, cm ³/g
30	1	40	2.64	**428.78**	0.809	1.484	2.1445	**0.2215**	0.2165	2.505	0.22016	1.3472	60.6240	0.218	275.36	**13.79**	1.84	1.405	323.40	**3.73**	1.536	3.63
				428.41								1.3338				**0.325**	0.15	0.033	313.6	**0.23**	0.0972	
				429.82								1.3351							313.6			
				428.10								1.3413							323.4			
				0.92								1.3576							343.0			
												1.3682										
30	1	60	2.64	**292.12**	0.787	1.465	2.165	**0.1185**	0.112	1.73	0.20128	1.3539	60.9273	0.198	302.70	**21.95**	1.75	2.238	445.90	**5.02**	2.51	3.3
				289.83								1.3526				**1.431**	0.13	0.146	450.8	**0.21**	0.1645	
				292.60								1.3531							431.2			
				293.92								1.3539							460.6			
				2.09								1.3546							441.0			
												1.3555										
30	1	80	2.64	**237.63**	0.817	1.532	2.218	**0.0755**	0.0705	1.055	0.19916	1.3604	61.2189	0.195	307.39	**28.65**	1.76	2.920	494.80	**6.04**	3.248	3.25
				236.98								1.3435				**1.056**	0.13	0.108	480.2	**0.28**	0.1454	
				238.96								1.3599							480.2			
				236.94								1.3641							509.6			
				1.15								1.3658							509.2			
												1.3688										
10	1	40	2.64	**633.45**	0.785	1.465	2.1515	**0.238**	0.241	2.575												
				630.45																		
				634.80																		
				635.10																		
				2.60																		
10	1	60	2.64	**437.15**	0.822	1.553	2.2745	**0.1505**	0.1415	2.01	0.20692	1.3474	60.6348	0.205	293.03	**14.89**	1.61	1.517	225.40	**3.72**	1.81	3.41

				440.24								1.3437				**0.974**	0.2	0.099	205.8	**0.35**	0.1294	
				435.21								1.3458							215.6			
				435.99								1.3472							225.4			
				2.71								1.3497							254.8			
												1.3508										
10	1	80	2.64	**296.90**	0.847	1.564	2.245	**0.085**	0.0775	1.205	0.19672	1.3166	59.2488	0.199	301.18	**22.43**	1.52	2.287	301.35	**5.09**	2.807	3.32
				298.66								1.3127				**0.824**	0.08	0.084	323.4	**0.25**	0.1445	
				296.90								1.3151							294.0			
				295.14								1.3175							294.0			
				1.76								1.3178							294.0			
												1.3201										
5	1	40	2.64	**725.50**	0.843	1.519	2.17	**0.2425**	0.2495	2.54												
				725.06																		
				725.65																		
				725.80																		
				0.39																		
5	1	60	2.64	**584.93**	0.877	1.578	2.2315	**0.178**	0.17	2.155												
				586.16																		
				583.26																		
				585.36																		
				1.50																		
5	1	80	2.64	**378.58**	0.853	1.595	2.296	**0.094**	0.09	1.26	0.20532	1.3394	60.2712	0.204	293.55	**17.76**	1.42	1.811	232.75	**3.86**	2.39	3.41
				374.28								1.3362				**0.866**	0.13	0.088	225.4	**0.24**	0.1294	
				380.15								1.3366							254.8			
				381.30								1.3396							225.4			
				3.77								1.3422							225.4			

												1.3422										
2	1	60	2.64	**724.01**	0.895	1.622	2.2955	**0.182**	0.18	2.095												
				720.92																		
				726.30																		
				724.80																		
				2.78																		
2	1	80	2.64	**560.74**	0.863	1.596	2.289	**0.108**	0.101	1.41												
				559.38																		
				561.62																		
				561.22																		
				1.19																		
10	1	23	2.64	**728.30**	0.823	1.508	2.169	**0.3005**	0.3145	2.830												
				729.08																		
				726.48																		
				729.35																		
				1.58																		
30	1	23	2.64	**606.09**	0.8575	1.5655	2.241	**0.3**	0.316	2.875												
				607.60																		
				603.94																		
				606.74																		
				1.91																		

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm²/g	stiffness, MNm/kg	bulk, cm³/g
30	1	40	3.72	**414.22**	0.806	1.463	2.095	**0.2165**	0.2115	2.51	0.21516	1.3791	62.0577	0.208	288.43	**15.67**	1.72	1.597	372.40	**4.07**	1.821	3.47
				412.86								1.3705				**1.140**	0.14	0.116	372.4	**0.00**	0.1223	
				415.61								1.3715							372.4			
				414.20								1.3833							372.4			
				1.38								1.3844							372.4			
												1.3856										
30	1	60	3.72	**273.47**	0.810	1.484	2.147	**0.1175**	0.112	1.71	0.19976	1.3358	60.1101	0.199	300.91	**22.16**	1.68	2.259	428.75	**4.8**	2.6611	3.32
				275.35								1.3318				**0.790**	0.18	0.081	431.2	**0.08**	0.9201	
				272.20								1.3324							421.4			
				272.87								1.3333							431.2			
				1.66								1.3379							431.2			
												1.3435										
30	1	80	3.72	**226.87**	0.824	1.533	2.243	**0.0745**	0.0705	1.04	0.19396	1.3629	61.3314	0.190	316.21	**29.63**	1.79	3.020	494.70	**6.02**	3.267	3.16
				226.50								1.3585				**1.221**	0.1	0.124	480.2	**0.20**	0.1333	
				226.90								1.3618							499.8			
				227.20								1.3629							490.0			
				0.35								1.3653							508.8			
												1.3661										
10	1	40	3.72	**582.21**	0.796	1.480	2.151	**0.2365**	0.2395	2.595	0.22416	1.2937	58.2165	0.231	259.71	**8.66**	1.59	0.883	134.75	**2.31**	1.015	3.85
				580.14								1.2616				**0.675**	0.12	0.069	127.4	**0.25**	0.09928	
				584.16								1.2619							127.4			
				582.34								1.3032							156.8			
				2.01								1.3045							127.4			
												1.3373										

10	1	60	3.72	**392.62**	0.823	1.509	2.168	**0.144**	0.137	1.975	0.20520	1.3638	61.3728	0.201	299.09	**17.11**	1.74	1.744	238.10	**3.88**	2.018	3.34
				393.05								1.3600				**0.519**	0.17	0.053	226.8	**0.22**	0.105	
				393.44								1.3606							254.2			
				391.38								1.3632							244.6			
				1.09								1.3674							226.8			
												1.3680										
10	1	80	3.72	**273.17**	0.864	1.606	2.329	**0.0825**	0.0795	1.18	0.20308	1.3477	60.6474	0.201	298.64	**23.50**	1.57	2.396	320.95	**5.29**	2.847	3.35
				272.81								1.3359				**1.033**	0.15	0.105	343.0	**0.33**	0.1806	
				272.88								1.3419							323.4			
				273.83								1.3469							323.4			
				0.57								1.3568							294.0			
												1.3571										
5	1	40	3.72	**697.43**	0.861	1.546	2.202	**0.2485**	0.255	2.595												
				695.66																		
				698.52																		
				698.10																		
				1.54																		
5	1	60	3.72	**505.05**	0.852	1.551	2.1865	**0.159**	0.151	2.025	0.22216	1.3289	59.8005	0.223	269.18	**11.76**	1.53	1.198	169.05	**2.83**	1.49	3.72
				504.50								1.3225				**0.879**	0.13	0.090	166.6	**0.08**	0.1201	
				505.94								1.3260							176.4			
				504.70								1.3299							166.6			
				0.78								1.3305							166.6			
												1.3356										
5	1	80	3.72	**333.02**	0.884	1.623	2.3095	**0.085**	0.0785	1.23	0.19684	1.3320	59.9409	0.197	304.52	**20.99**	1.5	2.140	240.10	**4.01**	2.642	3.28
				332.24								1.3242				**0.670**	0.1	0.068	225.4	**0.39**	0.06833	
				335.50								1.3288							215.6			

				331.31								1.3306							264.6			
				2.20								1.3373							254.8			
												1.3392										
2	1	60	3.72	**685.52**	0.890	1.602	2.322	**0.1775**	0.173	2.14												
				685.40																		
				681.60																		
				689.56																		
				3.98																		
2	1	80	3.72	**489.01**	0.887	1.621	2.295	**0.105**	0.099	1.375												
				488.24																		
				489.89																		
				488.90																		
				0.83																		
5	1	23	3.72	**748.06**	0.8405	1.4955	2.122	**0.293**	0.306	2.830												
				747.54																		
				749.65																		
				747.00																		
				1.40																		
10	1	23	3.72	**690.73**	0.836	1.5125	2.148	**0.3035**	0.321	2.805												
				689.02																		
				690.70																		
				692.46																		
				1.72																		
30	1	23	3.72	**556.29**	0.8385	1.5145	2.150	**0.282**	0.289	2.820												

				558.62																		
				554.36																		
				555.88																		
				2.16																		

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm ²/g	stiffness, MNm/kg	bulk, cm ³/g
30	1	60	4.57	**260.30**	0.868	1.595	2.265	**0.1225**	**0.12005**	1.785												
				260.66																		
				258.37																		
				261.88																		
				1.78																		
10	1	60	4.57	**357.60**	0.866	1.622	2.3315	**0.146**	**0.1405**	1.99												
				358.66																		
				355.65																		
				358.50																		
				1.69																		
5	1	60	4.57	**459.32**	0.877	1.597	2.2505	**0.172**	**0.1685**	2.17												
				457.90																		
				464.65																		
				455.40																		
				4.78																		
2	1	60	4.57	**626.83**																		
				630.30																		
				623.30																		

				626.90																		
				3.50																		

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm ²/g	stiffness, MNm/kg	bulk, cm ³/g
30	0.5	60	3.72	**306.69**	0.884	1.611	2.281	**0.135**	**0.1325**	1.845												
				304.44																		
				305.13																		
				310.49																		
				3.31																		
10	0.5	60	3.72	**468.11**	0.914	1.654	2.3245	**0.1575**	**0.153**	2.01												
				468.41																		
				466.71																		
				469.21																		
				1.28																		
5	0.5	60	3.72	**566.59**	0.887	1.630	2.3225	**0.1825**	**0.1785**	2.195												
				565.32																		
				567.17																		
				567.28																		
				1.10																		
2	0.5	60	3.72	**698.47**																		
				699.50																		
				699.70																		
				696.20																		
				1.97																		

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm ²/g	stiffness, MNm/kg	bulk, cm ³/g
30	2	40	3.72	**347.90**	0.841	1.545	2.22	**0.192**	**0.186**	2.425	0.21664	1.3499	60.7455	0.214	280.40	**15.23**	1.69	1.553	257.25	**4.23**	1.853	3.57
				349.10								1.3434				**0.448**	0.22	0.046	245.0	**0.15**	0.1389	
				346.63								1.3435							254.8			
				347.98								1.3489							264.6			
				1.24								1.3545							264.6			
												1.3592										
30	2	60	3.72	**264.23**	0.847	1.559	2.2145	**0.106**	**0.0995**	1.65	0.19672	1.3390	60.2541	0.196	306.29	**21.67**	1.72	2.209	316.05	**5.25**	2.546	3.26
				258.78								1.3318				**1.132**	0.08	0.115	303.8	**0.16**	0.1536	
				267.41								1.3340							313.6			
				266.51								1.3375							323.4			
				4.74								1.3452							323.4			
												1.3464										
30	2	80	3.72	**223.92**	0.867	1.607	2.2935	**0.0705**	**0.0665**	0.995	0.19224	1.3512	60.8040	0.190	316.29	**28.06**	1.65	2.626	333.30	**5.48**	3.103	3.16
				224.20								1.3424				**1.020**	0.14	0.104	323.4	**0.18**	0.118	
				222.25								1.3429							323.8			
				225.30								1.3495							343.0			
				1.54								1.3598							343.0			
												1.3614										
10	2	40	3.72	**482.10**	0.846	1.545	2.198	**0.2285**	**0.232**	2.62	0.22148	1.3492	60.7158	0.219	274.14	**10.93**	1.68	1.114	164.15	**2.70**	1.305	3.65
				478.60								1.3426				**0.923**	0.21	0.094	166.6	**0.15**	0.05977	
				483.20								1.3436							176.4			
				484.51								1.3455							156.8			
				3.10								1.3514							156.8			

												1.3631										
10	2	60	3.72	**325.20**	0.850	1.570	2.2535	**0.14**	**0.1365**	1.905	0.20360	1.3344	60.0471	0.203	294.93	**17.05**	1.61	1.738	232.75	**3.88**	2.019	3.39
				330.99								1.3253				**0.845**	0.1	0.086	215.6	**0.28**	0.1158	
				322.49								1.3293							225.4			
				322.12								1.3298							235.2			
				5.02								1.3437							254.8			
												1.3438										
10	2	80	3.72	**249.90**	0.854	1.591	2.265	**0.0745**	**0.068**	1.125	0.19272	1.3306	59.8779	0.193	310.70	**22.88**	1.53	2.333	318.50	**5.32**	2.881	3.22
				246.35								1.3256				**0.951**	0.17	0.097	323.4	**0.09**	0.07754	
				252.76								1.3283							313.6			
				250.60								1.3298							313.6			
				3.26								1.3312							323.4			
												1.3382										
5	2	40	3.72	**616.11**	0.859	1.546	2.2115	**0.2435**	**0.2495**	2.595												
				613.20																		
				619.74																		
				615.40																		
				3.33																		
5	2	60	3.72	**441.78**	0.856	1.585	2.277	**0.1505**	**0.1445**	2.03	0.20384	1.3474	60.6312	0.202	297.45	**14.89**	1.6	1.517	205.80	**3.39**	1.813	3.36
				444.62								1.3314				**1.178**	0.14	0.120	196.0	**0.23**	0.1877	
				438.82								1.3414							225.4			
				441.90								1.3516							196.0			
				2.90								1.3547							205.8			
												1.3577										
5	2	80	3.72	**298.62**	0.879	1.634	2.3335	**0.0885**	**0.0835**	1.25	0.19524	1.3394	60.2712	0.194	308.70	**22.11**	1.44	2.253	296.45	**4.92**	2.858	3.24

				294.89								1.3349				**1.273**	0.16	0.130	303.8	**0.16**	0.1457	
				302.76								1.3377							284.2			
				298.20								1.3389							294.0			
			td	**3.95**								1.3426							303.8			
												1.3427										

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index	thickness, mm	weight, g	grammage, g/m ²	normalized thickness, mm	sheet density, kg/m ³	tensile index, Nm/g	stretch, %	breaking length, km	tear strength, mN	tear index, mNm ²/g	stiffness, MNm/kg	bulk, cm ³/g
30	3	40	3.72	**331.45**	0.864	1.560	2.2155	**0.174**	**0.173**	2.335	0.19664	1.3181	59.3163	0.199	301.65	**17.08**	1.78	1.741	274.41	**4.63**	2.041	3.32
				334.46								1.3076				**0.890**	0.15	0.091	284.2	**0.23**	0.1592	
				328.20								1.3138							284.2			
				331.70								1.3194							274.4			
				3.14								1.3234							254.8			
												1.3265										
30	3	60	3.72	**248.45**	0.875	1.619	2.3125	**0.1005**	**0.097**	1.5	0.19652	1.3467	60.6015	0.195	308.37	**21.88**	1.63	2.231	294.00	**4.85**	2.721	3.24
				248.50								1.3441				**1.213**	0.12	0.124	284.2	**0.13**	0.1116	
				245.50								1.3459							294.0			
				251.34								1.3461							294.0			
				2.92								1.3484							303.8			
												1.3490										
30	3	80	3.72	**220.02**	0.842	1.622	2.3375	**0.0735**	**0.0685**	1.02	0.18212	1.3436	60.4629	0.181	331.99	**27.04**	1.62	2.757	372.25	**6.16**	3.174	3.01
				221.90								1.3420				**1.192**	0.14	0.122	382.2	**0.30**	0.128	
				219.05								1.3423							362.6			
				219.10								1.3436							392.0			
				1.63								1.3441							352.2			
												1.3461										

10	3	40	3.72	**432.89**	0.871	1.555	2.189	**0.2195**	**0.2195**	2.53	0.21408	1.3225	59.5134	0.216	278.00	**12.40**	1.66	1.264	173.95	**2.92**	1.468	3.6
				427.80								1.3064				**0.730**	0.15	0.074	166.6	**0.16**	0.07467	
				433.80								1.3133							166.6			
				437.06								1.3240							186.2			
				4.70								1.3342							176.4			
												1.3347										
10	3	60	3.72	**297.90**	0.857	1.578	2.232	**0.1205**	**0.118**	1.77	0.20676	1.3478	60.6492	0.205	293.33	**17.69**	1.65	1.803	257.25	**4.24**	2.224	3.41
				296.27								1.3380				**1.241**	0.18	0.127	245.0	**0.31**	0.1314	
				299.13								1.3424							284.2			
				298.30								1.3486							254.8			
				1.47								1.3514							245.0			
												1.3584										
10	3	80	3.72	**235.87**	0.876	1.602	2.2695	**0.077**	**0.0725**	1.12	0.19444	1.3443	60.4917	0.193	311.11	**23.58**	1.63	2.404	330.75	**5.47**	2.983	3.21
				234.00								1.3338				**1.424**	0.19	0.145	352.8	**0.33**	0.1199	
				236.00								1.3421							343.0			
				237.60								1.3478							313.6			
				1.80								1.3482							313.6			
												1.3494										
5	3	40	3.72	**544.34**	0.835	1.546	2.2335	**0.226**	**0.2245**	2.51												
				547.06																		
				544.96																		
				541.00																		
				3.08																		
5	3	60	3.72	**385.36**	0.864	1.576	2.23	**0.1435**	**0.1385**	1.95	0.20360	1.3258	59.6619	0.205	293.03	**16.69**	1.61	1.702	226.55	**3.80**	2.038	3.41
				386.58								1.3160				**0.921**	0.11	0.094	215.6	**0.27**	0.1042	
				387.68								1.3239							245.0			

				381.81								1.3286							235.2			
				3.12								1.3264							210.4			
												1.3342										
5	3	80	3.72	**272.75**	0.845	1.603	2.354	**0.089**	**0.0845**	1.23	0.18720	1.3352	60.0822	0.187	320.95	**23.27**	1.51	2.372	303.80	**5.06**	2.915	3.12
				272.01								1.3305				**1.492**	0.13	0.152	303.8	**0.27**	0.1406	
				273.66								1.3309							284.2			
				272.58								1.3327							303.8			
				0.84								1.3368							323.4			
												1.3449										

time, min	**consistency, %**	**temperature, °C**	**energy intensity, W/kg-suspension**	**freeness, g**	**mean length (arithmetic), mm**	**mean length (length weighted), mm**	**mean length (weight weighted), mm**	**mean curl index (arithmetic)**	**mean curl index (length weighted)**	**mean kink index**	**thickness, mm**	**weight, g**	**grammage, g/m ²**	**normalized thickness, mm**	**sheet density, kg/m ³**	**tensile index, Nm/g**	**stretch, %**	**breaking length, km**	**tear strength, mN**	**tear index, mNm ²/g**	**stiffness, MNm/kg**	**bulk, cm ³/g**
30	4	60	3.72	**238.02**	0.855	1.604	2.3435	**0.1005**	**0.101**	1.455	0.19592	1.3412	60.3549	0.195	308.06	**21.57**	1.74	2.097	333.20	**5.52**	2.544	3.25
				240.48								1.3306				**1.056**	0.15	0.108	313.6	**0.27**	0.1185	
				236.16								1.3331							352.8			
				237.42								1.3444							333.2			
			std	**2.22**								1.3458							333.2			
												1.3522										
10	4	60	3.72	**281.32**	0.847	1.578	2.273	**0.116**	**0.1145**	1.69	0.19860	1.3129	59.0823	0.202	297.49	**17.66**	1.73	1.800	276.85	**4.69**	2.218	3.36
				281.87								1.3036				**0.921**	0.09	0.094	264.6	**0.21**	0.1742	
				281.90								1.3068							274.4			
				280.20								1.3132							294.0			
			std	**0.97**								1.3199							274.4			
												1.3212										

5	4	60	3.72	**362.72**	0.826	1.547	2.276	**0.1415**	**0.142**	1.925												
				364.36																		
				362.31																		
				361.50																		
			std	**1.47**																		

Appendix C

Latency Removal Kinetics Matlab Code

```
%% Main program for nonlinear parameter identification using "fminsearch"

%  initial set-up
clear all; close all; clc

p0      = [2*10^8 4000 1.4 1.2 2]';
options = optimset('Display','iter','MaxFunEvals', 3000, 'TolX',0.1,'TolFun', 0.01,'MaxIter',
1500);
result  = fminsearch(@modelpara,p0,options);
for i = 1:5
   disp(result(i))
end
save


%%%%%%%%%%%%%%%%
%% Ordinary differential equation
% dF   = model (F, d, p0)
% t    : time
% F    : variable
% d    : data (or measurements)
% p0   : vector of initial parameter values
% dF   : differential value of F

function dF = model(t,F)

global d p0 F0 Ff

% parameters
k0      = p0(1);
lambda0 = p0(2);
a0      = p0(3);
beta0   = p0(4);
n       = p0(5);

% measurements
ep      = d(1);          % power intensity ( W/kg-suspension)
cm      = d(2);          % consistency (%)
T       = d(3);          % temperature (C)

% auxiliary
```

```
k = -k0*exp(-lambda0/T)*ep^a0*cm^beta0;
% ODE
dF = k*((F-Ff)/(F0-Ff))^n;
end


%%%%%%%%%%%%%
%% Calculate square residuals

% initial set-up
function [Fss] = modelpara(kp)
load mydata.txt;
n          = length(mydata);
Ttime   = mydata(:,4);

% global variables
global d p0 F0 Ff

p0       = kp;
F0       = 819.9;
Ff       = 220.02;

% model prediction
dfinal  = n;
for i = 1:dfinal
    d                  = mydata(i,1:3);
    tspan              = [0 Ttime(i)];
   [T Fbar]            = ode45(@model,tspan,F0);
   Fpredict(i,1)    = Fbar(end);

end

% residual square
 Fss     = norm(Fpredict - mydata(1:dfinal,5));


%%%%%%%%%%%%%
%% Calculate square residuals
clear all; clc; close all;

load mydata.txt;

n          = length(mydata);
Ttime   = mydata(:,4);

load matlab.mat
```

```
global d p0 F0 Ff

p0  = result;
F0  = 819.9;
Ff  = 220.02;

% model prediction
dfinal = n;
for i = 1:dfinal
    d              = mydata(i,1:3);
    tspan          = [0 Ttime(i)];
   [T Fbar]        = ode45(@model,tspan,F0);
   Fpredict(i,1)   = Fbar(end);

end

% plots
TTime = 1:n;
figure(1)
plot(TTime,Fpredict,TTime,mydata(:,5));
legend('predicted','measured')
grid

figure(2)
x=200:200:800;
y=x;
plot(Fpredict,mydata(:,5),'o',x,y);
xlabel('Freeness (predicted)');
ylabel('Freeness (measured)');


%%%%%%%%%%%
%% mydata
3.72   0.5 333 2    698.47
3.72   0.5 333 5    566.59
3.72   0.5 333 10   468.11
1.89   1   333 2    748.86
1.89   1   333 5    637.02
1.89   1   333 10   498.08
2.64   1   296 10   728.30
2.64   1   296 30   606.09
2.64   1   313 5    725.50
2.64   1   313 10   633.45
2.64   1   313 30   428.78
2.64   1   333 2    724.01
```

2.64	1	333	5 584.93
2.64	1	333	10 437.15
2.64	1	333	30 292.12
2.64	1	353	2 560.74
2.64	1	353	5 378.58
2.64	1	353	10 296.90
2.64	1	353	30 237.63
3.72	1	333	2 685.52
3.72	1	333	5 505.05
3.72	1	333	10 392.62
4.57	1	333	2 626.83
4.57	1	333	5 459.32
4.57	1	333	10 357.60
3.72	2	333	5 441.78
3.72	2	333	10 325.20
3.72	3	333	5 385.36
3.72	3	333	10 297.90
3.72	4	333	5 362.72
3.72	4	333	10 281.32

Appendix D

Experimental Data on Latency Removal of Secondary BCTMP Pulp

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index
0	1	23	0.000	**818.65**	0.777	1.359	1.9455	**0.306**	**0.334**	2.755
				819.16	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				817.60						
				819.20						
				0.91						
2	1	40	1.89	**723.17**	0.871	1.503	2.0895	**0.271**	**0.277**	2.725
				721.54	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				725.16						
				722.80						
				1.84						
5	1	40	1.89	**613.58**	0.831	1.464	2.0805	**0.246**	**0.2505**	2.67
				616.65	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				610.68						
				613.40						
				2.99						
10	1	40	1.89	**537.75**	0.856	1.485	2.073	**0.23**	**0.232**	2.59
				534.10	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				537.20						
				541.96						
				3.96						
30	1	40	1.89	**450.68**	0.888	1.573	2.2115	**0.203**	**0.2035**	2.49

				449.79						
				453.44						
				448.80						
				2.44						
0.5	1	60	1.89	**720.95**	0.887	1.536	2.142	**0.2065**	**0.2075**	2.34
				719.86	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				721.62						
				721.36						
				0.95						
1	1	60	1.89	**629.35**	0.863	1.516	2.112	**0.1775**	**0.175**	2.16
				628.52	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				630.32						
				629.20						
				0.91						
2	1	60	1.89	**534.57**	0.859	1.515	2.1325	**0.1595**	**0.1575**	2.115
				537.35	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				532.64						
				533.73						
				2.47						
5	1	60	1.89	**438.97**	0.861	1.524	2.153	**0.137**	**0.131**	1.92
				436.59						
				440.52						
				439.80						
				2.09						
30	1	60	1.89	**317.56**	0.874	1.562	2.216	**0.0885**	**0.0855**	1.395
				319.11						
				313.19						
				320.37						
				3.83						

0.5	1	85	1.89	**415.43** **412.70** **418.33** **415.26** **2.82**	0.881	1.593	2.275	**0.072**	**0.068**	1.03
1	1	85	1.89	**351.47** **355.05** **349.41** **349.96** **3.11**	0.896	1.618	2.2995	**0.0695**	**0.067**	0.99
1.5	1	85	1.89	**326.59** **332.08** **327.30** **320.40** **5.87**	0.858	1.526	2.1585	**0.0695**	**0.0655**	1
5	1	85	1.89	**290.02** **289.85** **286.74** **293.46** **3.36**	0.871	1.584	2.252	**0.06**	**0.057**	0.835

time, min	**consistency, %**	**temperature, °C**	**energy intensity, W/kg-suspension**	**freeness, g**	**mean length (arithmetic), mm**	**mean length (length weighted), mm**	**mean length (weight weighted), mm**	**mean curl index (arithmetic)**	**mean curl index (length weighted)**	**mean kink index**
0	1	23	0.000	**818.65** **819.16** **817.60** **819.20**	0.777 BSD 5 min	1.359 BSD 5 min	1.9455 BSD 5 min	**0.306** BSD 5 min	**0.334** BSD 5 min	2.755 BSD 5 min

				0.91						
0.5	1	60	2.64	**697.23**	0.846	1.491	1.1095	**0.208**	**0.207**	2.355
				696.30	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				697.80						
				697.60						
				0.81						
1	1	60	2.64	**605.49**	0.888	1.553	1.664	**0.183**	**0.1835**	2.25
				608.30	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				603.28						
				604.88						
				2.56						
2	1	60	2.64	**516.68**	0.882	1.524	1.1125	**0.1595**	**0.16**	2.095
				519.88	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				514.36						
				515.80						
				2.86						
5	1	60	2.64	**418.92**	0.862	1.550	1.2135	**0.133**	**0.131**	1.92
				423.78						
				418.30						
				414.68						
				4.58						
0.5	1	85	2.64	**377.13**	0.865	1.572	2.255	**0.072**	**0.067**	1.045
				375.99						
				379.34						
				376.05						
				1.92						
1	1	85	2.64	**339.70**	0.875	1.576	2.2515	**0.068**	**0.0625**	0.96
				343.05						
				336.01						

				340.05						
				3.53						
5	1	85	2.64	**282.88**	0.868	1.576	2.2605	**0.0565**	**0.053**	0.815
				283.50						
				285.74						
				279.40						
				3.22						

time, min	**consistency, %**	**temperature, °C**	**energy intensity, W/kg-suspension**	**freeness, g**	**mean length (arithmetic), mm**	**mean length (length weighted), mm**	**mean length (weight weighted), mm**	**mean curl index (arithmetic)**	**mean curl index (length weighted)**	**mean kink index**
0	1	23	0.000	**818.65**	0.777	1.359	1.9455	**0.306**	**0.334**	2.755
				819.16	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				817.60						
				819.20						
				0.91						
5	1	40	3.72	**554.70**	0.873	1.508	2.0995	**0.242**	**0.2495**	2.585
				556.70	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				553.30						
				554.10						
				1.78	0.851	1.502	2.1125	**0.2435**	**0.251**	2.625
0.5	1	60	3.72	**642.08**	0.882	1.556	2.1985	**0.189**	**0.189**	2.275
				643.65	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				640.90						
				641.70						
				1.41	0.861	1.525	2.165	**0.186**	**0.1875**	2.245
1	1	60	3.72	**574.87**	0.891	1.564	2.2025	**0.1675**	**0.164**	2.18
				576.50	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min

				573.12 **575.00** **1.69**	0.886	1.565	2.188	**0.1725**	**0.1725**	2.135
2	1	60	3.72	**485.26** **484.80** **486.09** **484.90** **0.72**	0.879	1.546	2.1815	**0.1565**	**0.1515**	2.075
5	1	60	3.72	**395.74** **398.72** **393.30** **395.20** **2.75**	0.873	1.535	2.1525	**0.1225**	**0.119**	1.795
0.5	1	85	3.72	**371.35** **372.20** **370.00** **371.85** **1.18**	0.846	1.534	2.209	**0.072**	**0.068**	1.04
1	1	85	3.72	**341.06** **342.70** **340.39** **340.10** **1.42**	0.856	1.562	2.273	**0.068**	**0.065**	0.96
5	1	85	3.72	**279.38** **278.60** **279.54** **280.00** **0.71**	0.859	1.554	2.2045	**0.0575**	**0.054**	0.815

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index
0	2	23	0.000	**818.65**	0.777	1.359	1.9455	**0.306**	**0.334**	2.755
				819.16	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				817.60						
				819.20						
				0.91						
0.5	2	60	3.72	**624.80**	0.853	1.492	2.0955	**0.1855**	**0.184**	2.25
				625.80	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				625.20						
				623.40						
				1.25						
1	2	60	3.72	**518.02**	0.873	1.531	2.144	**0.161**	**0.1585**	2.135
				519.33	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				516.34						
				518.40						
				1.53						
2	2	60	3.72	**436.14**	0.865	1.538	2.1645	**0.136**	**0.1345**	1.935
				434.02						
				435.70						
				438.70						
				2.37						
5	2	60	3.72	**354.84**	0.863	1.534	2.162	**0.1155**	**0.1125**	1.81
				357.65						
				354.98						
				351.90						
				2.88						

time, min	consistency, %	temperature, °C	energy intensity, W/kg-suspension	freeness, g	mean length (arithmetic), mm	mean length (length weighted), mm	mean length (weight weighted), mm	mean curl index (arithmetic)	mean curl index (length weighted)	mean kink index
0	3	23	0.000	**818.65**	0.777	1.359	1.9455	**0.306**	**0.334**	2.755
				819.16	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				817.60						
				819.20						
				0.91						
5	3	23	3.72	**559.53**	0.836	1.476	2.0925	**0.2625**	**0.2755**	2.71
				558.07	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				559.81						
				560.70						
				1.34						
30	3	23	3.72	**411.74**	0.870	1.530	2.1505	**0.192**	**0.1945**	2.425
				408.69	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				415.69						
				410.85						
				3.58						
0.5	3	60	3.72	**561.65**	0.861	1.524	2.1495	**0.166**	**0.165**	1.99
				562.22	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min	BSD 5 min
				560.32						
				562.40						
				1.15						
1	3	60	3.72	**478.79**	0.861	1.514	2.127	**0.1395**	**0.137**	1.93
				478.16						
				478.86						
				479.36						
				0.60						

2	3	60	3.72	**403.77** **401.20** **405.10** **405.00** **2.22**	0.874	1.531	2.135	**0.1285**	**0.1255**	1.855
5	3	60	3.72	**325.86** **326.86** **324.93** **325.80** **0.97**	0.853	1.531	2.1695	**0.0955**	**0.0955**	1.47
0.5	3	85	3.72	**343.01** **339.23** **341.68** **348.12** **4.59**	0.861	1.565	2.2515	**0.0685**	**0.065**	0.96
1	3	85	3.72	**311.66** **311.12** **311.12** **312.75** **0.94**	0.836	1.523	2.2265	**0.061**	**0.056**	0.835
5	3	85	3.72	**269.90** **273.35** **269.39** **266.96** **3.23**	0.905	1.600	2.2395	**0.0535**	**0.05**	0.725
10	3	85	3.72	**268.68** **266.71** **269.54** **269.78**	0.822	1.518	2.213	**0.051**	**0.0465**	0.645

				1.71						
30	3	85	3.72	**268.25**	0.879	1.577	2.235	**0.049**	**0.046**	0.585
				269.53						
				263.99						
				271.22						
				3.78						

Appendix E

Industrial Latency Removal of the Pulp Suspension within the Mixing Zone

```
% TMP in HSPP
% Temperature=80°C;
% Consistency=4.5%;
% Estimated power input=200HPx80%;
% Suspension volume=241.7m ³

% Initial freeness=819.9mL;
% Final freeness=220.02mL

A = ezplot('t*3.4*10^8*exp(-5430/353)*(200*0.8*0.746/241.7)*(4.5^0.65)*((y-220.02)/(819.9-220.02))^1.5 +
(y-220.02)/(819.9-220.02) - 1',[0 1 200 800]);

set(A, 'Color', 'b');

hold on

% CTMP in QRP
% Temperature=80°C;
% Consistency=4%;
% Estimated power input=225HPx80%;
% Suspension volume=313.7

% Initial freeness=818.65mL;
% Final freeness=268.25mL

B = ezplot('t*3.1*10^15*exp(-10017/353)*(225*0.8*0.746/313.7)^0.35*(4^0.65)*((y-268.25)/(818.65-
268.25))^2 + (y-268.25)/(818.65-268.25) - 1',[0 1 270 800]);

set(B, 'Color', 'r');
```