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EFFECT OF SELECTED FILLING AND PULP SUSPENSION VARIABLES IN IMPROVING THE PERFORMANCE OF LOW-CONSISTENCY REFINING

Doctoral Thesis

Kari Koskenhely

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DOCTORAL THESIS

Kari Koskenhely

Helsinki University of Technology, Laboratory of Paper and Printing Technology, Espoo, Finland

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ABSTRACT

This thesis comprises the main findings of a study aiming to improve the performance of low-consistency refining. The following areas were studied: the reproducibility of the laboratory refiner used in the experiments; the refining characteristics of softwood kraft fibre fractions; and the effect of the refiner configuration and bar edge sharpness on fibre and handsheet properties.

Careful and regular estimation of no-load power is important for the reproducibility of a laboratory refiner's performance. The warm-up time affects the level of no-load power of the laboratory refiner. Thus, before recording the estimate of no-load power the refiner needs to warm up and approach steady state. At low 0.3 J/m intensity refining, already a 12% change in no-load power, which was caused by reduced warm-up time, was found to cause significant variability in the refining result.

In the refining of softwood kraft fibre fractions, optimising refining intensity is important since a fraction having shorter fibre length may have reduced load-carrying capacity. The short-fibre fraction did not tolerate the high intensity of 3.7 J/m as the original pulp and long-fibre fraction did. In addition, more severe fibre shortening of the short-fibre fraction started at lower intensity than what is typically expected for softwood pulp. The magnitude of the gap was found to depend on the type of fraction, with the short-fibre fraction forming a narrower gap than the original pulp and long-fibre fraction at a given intensity. The fraction-specific intensity and gap behaviour are believed to be related to the compressibility of fibre flocs under the stress exerted by the bar surfaces. The specific energy input determined the increase in fibre swelling which contributed to a higher sheet density and improved tensile strength.

When examining the differences in refining result between the disc and conical configuration, the conical configuration seemed to form a wider gap than the disc configuration when long-fibre softwood kraft was refined. The reason for this could not be determined. In addition, conical fillings shortened fibres less at medium and high intensity. The sharp bar leading edge of disc fillings was probably the reason for the more severe fibre shortening, which supports earlier findings that refining intensity and bar edge sharpness determine the degree of fibre shortening. By introducing a new method to study bar edge profile, new numerical information was gained on bar edge sharpness. A small calculated radius for the bar edge together with small size angular shaped profiles in the bar edge area appeared to cause the most severe fibre shortening. To avoid

severe shortening of long softwood fibres and to retain the energy efficiency of refining, the bar leading edge profile should have radius of curvature fitted to the bar edge larger than about 80 micrometers, but not much more because that may reduce energy efficiency. Small size flaws in bar edges, such as scratches after machining should be removed by a careful finishing of fillings. Both the sharp bar edge and scratches are assumed to hold fibres, causing a tensile-type fibre failure mechanism to occur more easily. The wear and rounding of bar edges depends on the material composition of the fillings. For this reason, care should be taken in selecting a suitable filling material for refining long-fibre softwood pulps.

TIIVISTELMÄ

Kemiallisen massan jauhatus on eräs laajimmin ja ajallisesti pitkään tutkittu paperinvalmistuksen osa-alue, jonka mekanismit ovat osittain heikosti tunnettuja. Vaillinnainen ymmärrys yhdessä vaikeasti mitattavien kuitutason jauhatusvaikutusten kanssa on johtanut jauhatuskäytäntöjen ajoittain liian pitkälle vietyyn yksinkertaistukseen ja yleistykseen. Näistä lähtökohdista muodostui työn tausta-ajatus ja yleistavoite; jauhatusta ei pidä yleistää liikaa, vaan kemiallisen massan kuituflokkien käyttäytyminen jauhinterävälissä on yksilöllistä, johon käytetty kuitutyyppi ja sen dimensiot; esim. kuitupituus vaikuttaa. Tämä edellyttääkin tietyn kuitutyypin jauhatuksen huolellista optimointia. Havupuusellun fraktiointi nähtiin mahdollisuudeksi jakaa alkuperäinen sulppu kuitudimensioiltaan ja flokkaantumiseltaan erilaisiin jakeisiin. Näiden jauhatuskäyttäytyminen on aiemmin kartoitettu epätäydellisesti. Vastaavasti jauhiteräparametereista terän johtavan teräsärmän pyöreyden vaikutus kuitujen lyhentymisessä, sen numeerinen arvo ja mittaaminen havaittiin puutteellisesti tunnetuksi ja nykyjauhatuksessa osittain unohdetuksi parametriksi ja siten tutkimisen arvoiseksi. Työn yleistavoitteena olikin parantaa matalasakeusjauhatuksen suorituskykyä selvittämällä yllämainitun aihepiirin tekijöiden vaikutusta jauhatuskäyttäytymiseen-jauhinteräväliin ja kuituominaisuuksien kehittymiseen jauhatuksessa.

Väitöskirjan yhteenveto-osa kokoaa kokeellisen työn tärkeimmät tulokset ja johtopäätökset. Kokeellinen työ koostui kolmesta eri osa-alueesta; uuden matalasakeus-laboratoriojauhimen toistettavuuden arvioinnista ja tyhjäkäyntitehon mittauksen määrittelystä, havupuusellufraktioiden jauhatuskäyttäytymisen kartoittamisesta ja jauhatusparametrien optimoinnista ja jauhinteräkonfiguraation ja jauhinterän johtavan teräsärmän pyöreyden mittauksesta ja sen merkityksen arvioinnista pitkäkuituisen havupuusellun jauhatuksessa.

Jauhatuksen toistettavuuden kannalta riittävä esikäyttöaika havaittiin merkittäväksi parametriksi. Ennen tyhjäkäyntitehon rekisteröintiä jauhimen tulee lämmetä ja lähestyä tasapainotilaa, jotta riiittävän tarkka tyhjäkäyntitehoestimaatti saavutetaan. Jauhettaessa alhaisella 0.3 J/m intensiteetillä jo 12 % poikkeama rekisteröidyssä tyhjäkäyntitehossa aiheutti merkittävää vaihtelua kuitu- ja paperiominaisuuksissa. Laboratorio-olosuhteissa tyhjäkäyntitehonmääritys tulee olla päivittäinen toimenpide.

Pitkäkuituisen havupuusellun fraktioista painesihtilajittelun aksepti eli lyhytkuitufraktio osoitti poikkeavaa jauhatuskäyttäytymistä. Lyhytkuitufraktion

maksimi jauhatusintensiteetti oli selvästi alhaisempi kuin alkuperäisen massan tai pitkäkuitufraktion. Vastaavasti lyhytkuitufraktion kuitujen katkeilu voimistui skandinaaviselle havupuumassalle alhaisessa jauhatusintensiteetissä. Kuitujen katkeilu voimistui 2.4 J/m intensiteetissä, kun muilla fraktioilla lyhentyminen vastaavassa jauhatusintensiteetissä oli maltillista. Myös jauhinteräpintojen välinen teräväli oli pienempi tietyssä jauhatusintensiteetissä, kun lyhytkuitufraktiota jauhettiin. Tämän fraktio-ominaisen jauhatuskäyttäytymisen uskotaan johtuvan flokkirakenteesta ja flokin ja sen kuitujen kokoonpuristumisesta teräsärmien ja pintojen aikaansaamassa kuormituksessa. Tulokset kannustavat jauhatusintensiteetin huolelliseen optimointiin, etenkin jos massan kuitupituutta muutetaan tai suunnitellaan fraktioidun massan jauhatusta.

Kartio- ja levyterävertailussa kartioteräjauhatuksen terärako vaikutti suuremmalta. Kyseistä ilmiötä ei tuloksista pystytty selittämään. Uutta numeerista informaatiota saatiin tutkittaessa teräsärmän profiilin roolia havupuukuitujen lyhentymisessä. Kun johtavan teräsärmän profiiliin sovitetun ympyrän halkaisija on pieni tai jos profiili sisältää kulmikkaita pienen mittakaavan muutoksia niin riski voimakkaalle kuitujen lyhentymiselle lisääntyy. Kulmikkaat mittausprofiilin muutokset voivat olla esimerkiksi naarmuja tai rosoja, jotka ovat peräisin jauhinterien valun ja viimeistelyn jäljiltä. Tulosten perusteella skandinaavisen pitkäkuituisen havupuusellun kuitupituuden säilyttämiseksi ja jauhatuksen energiatehokkuuden varmistamiseksi, pitäisi teräsärmään sovitetun ympyrän halkaisija olla suurempi kuin 80 mikrometriä, mutta ei paljon tätä suurempi, koska liiallisen pyöristymisen myötä voi jauhatuksen energiatehokkuus heiketä. Jauhinterien materiaalivalintoihin ja niiden kulumiskäyttäytymiseen tulisikin kiinnittää nykyistä enemmän huomiota.

PREFACE

When I joined HUT and the Laboratory of Paper Technology in February 2002, I was given about three months to grasp the literature dealing with low-consistency refining of chemical pulp. After that period, the brand new Voith laboratory refiner would arrive and I would need to get familiar with the device and start experimental laboratory work. I wish to express my gratitude to Professor Hannu Paulapuro for giving me those three months to read and assimilate part of the vast refining literature. After this reading session, I had formed a sort of mental picture of refining which later helped me a lot in planning experiments and reviewing other yet untouched literature. Thus, in a way, these first three months formed a good basis for the forthcoming work. I would also like to acknowledge Professor Paulapuro for putting the laboratory's resources at the disposal of the project. Without the laboratory's skilful personnel, who helped me with the fibre and paper analyses, it would have been impossible to achieve the good results of the MAMI project. Leena Nolvi, Eija Korhonen, Harri Jaronen and the enthusiastic M.Sc. student Phichit Somboon (now working on his PhD) are just a few of the people whom I am indebted to. Dr. Eero Hiltunen is acknowledged for his support during the first year of the project, and Dr. Xinshu Wang for the years in the MAMI project. Dr. Ari Ämmälä and Hanna Jokinen from the University of Oulu and Kaarlo Nieminen from HUT, who contributed to a couple of my publications, are gratefully acknowledged. I would also like to thank Olof Andersson for checking the language of my manuscripts.

Among the sponsors' representatives, Pirkko Liias of Botnia, Paul Sepke of Voith Paper, Petri Silenius of M-real, Nina Ruohoniemi of Stora-Enso and Mikko Ylhäisi of TEKES are acknowledged. The comprehensive financial input allowed me to execute a wide range of scientific experiments and also report them in international conferences and magazines. Especially, I would like to thank Pirkko Liias for her encouraging feedback and Paul Sepke for introducing me to the laboratory refiner's mechanics and operation.

I was privileged to have several inspiring colleagues to share my thoughts with. Professor Paulapuro introduced me to the world of philosophy of science – an interesting area that was very motivating for my work and a source of invaluable information. Sharing an office with Kimmo Koivunen, we were often chatting on scientific problems and unexpected twists in the project management involving government money. I would like to thank Kimmo for those delightful moments and Juha Happonen for sharing many breaks with me,

while enjoying a cup of espresso. Frank Becherer is gratefully acknowledged for his great team work in studying the project business. I am grateful to Paula for her encouragement, good humour and fabulous company, and to my parents who gave me much-appreciated mental support. My sister Mari and her family I remember kindly for giving me a relaxing time during summer holidays. Thanks are also due to my friends for spending time with me during golf matches, music, poker evenings and lots of other activities. In the future, I wish I'll learn to know you better, dear Amanda.

Finally, I felt privileged to be able to spend time learning totally new things outside my specific research topic: some programming, some mathematics and physics, some philosophy and some tools for project management. This was my personal aim when embarking on post-graduate studies: to learn something new and develop new tools. In this respect, I feel mental comfort, but the omnivorous reader in me is still there. It seems that today's world forces most people to spend a large part of their time with urgent daily problems, which prevents them from reading literature and studying new things. Naturally, there are exceptions and variations in people’s personal drive. I see post-graduate studies as an opportunity to develop one’s personality and increase one’s knowledge in many ways and in a wider context. If you, the reader of this text, are heading for PhD studies, I warmly recommend that you grasp this opportunity, too.

"Beating is an art, the more refined for the higher grades of paper. As an art, beating is like the art of sailing a yacht or playing the game of tennis;.."

-A.B. Green, 1917.

ABBREVIATIONS, TERMS AND SYMBOLS

CEL – cutting edge length (km/rev)

CF – coarse-fibre fraction

CWT – cell-wall thickness

Configuration – the two major refiner types: conical and disc configuration

FF – fine-fraction from hydrocyclone

Filling micro structure – dimensions in tens of micrometers

Filling macro structure – dimensions in millimetres

FSP – fibre saturation point

HWK – hardwood kraft pulp from a Scandinavian pulp mill

LC-refiner – low-consistency refiner

L_s – cutting speed of filling (km/s)

LF – long-fibre fraction

Magnitude of gap – position of stator of laboratory refiner could be recorded. Its changes were used as an indicator of the gap. The absolute gap could not be recorded.

P_e – estimated effective refining power treating fibres (kW)

P_{n-l} – estimated no-load power (kW)

P_t – total measured refining power (kW)

PLC – process logic controller

Refiner behaviour – defined as "changes in magnitude of refiner gap"

SEL – specific edge load (J/m)

SEC – specific energy, net (kWh/t)

SF– short-fibre fraction

SWK – softwood kraft pulp from a Scandinavian pulp mill or original pulp before pressure-screen fractionation

$SWK_{\_Hc}$ – original pulp before hydrocyclone fractionation

LIST OF PUBLICATIONS

I. Koskenhely K., Somboon P., Paulapuro H., Reproducibility of refiner performance. Pulp & Paper Canada, 107(2006):7/8, 46-50.

II. Koskenhely K., Ämmälä A., Jokinen H., Paulapuro H., Effect of refining intensity on pressure screen fractionated softwood kraft. Nordic Pulp and Pap. Res. J., No:2/2005, 169-175, Errata, Nordic Pulp and Pap. Res. J., No:4/2005, 505.

III. Koskenhely K., Ämmälä A., Jokinen H., Paulapuro H., Refining characteristics of softwood fibre fractions. 13th Fundamental Research Symposium, Cambridge, UK, Vol 1, p. 427-456 and Vol 3, 1457-1460. Sep 2005.

IV. Koskenhely K., Nieminen K., Hiltunen E., Paulapuro H., Comparison of plate and conical fillings in refining of bleached softwood and hardwood pulp. Pap. ja Puu 87(2005):7, 458-463.

V. Koskenhely K., Nieminen K., Paulapuro H., Edge form profile of refiner filling bars and its impact on softwood fibre shortening. August 3, 2006 accepted for publication in Pap. ja Puu.

AUTHOR'S CONTRIBUTION

I. Design and analysis of experiments, a major part of pulp refining, first version of the manuscript.

II. Design and analysis of experiments except for the procedure for fractionation, refining the pulp, first version of the manuscript except the description of the fractionation procedure.

III. Design and analysis of experiments except the procedure for fractionation, refining the pulp, first version of the manuscript except the description of the fractionation procedure.

IV. Design and analysis of experiments, refining the pulp, first version of the manuscript except the description of the calculation of the radius fitted to the bar edge.

V. Design and analysis of experiments, major part of pulp refining, specification for the profilometer measurement, first version of the manuscript except the description of the calculation of the bar edge form profile.

INTRODUCTION

Low-consistency refining of chemical pulp means mechanical treatment of wood fibres in a suspension consisting of water and fibres. Fibre flocs are subjected to cyclic impacts by moving rotor bars and are compressed and sheared strongly between the bar surfaces and the bar edges. As a result, the fibre structure changes permanently. The different structural changes have been widely studied, and listed in review papers (Ebeling 1980, Page 1989). The structural changes caused in the refiner consist of internal fibrillation, fibre shortening, external fibrillation and fines formation. Recently, fibre straightening as a primary refining effect has been added to this list (Mohlin and Miller 1992, Mohlin and Miller 1995, Seth 2006).

Based on research done in laboratories we know to what extent structural changes in SWK fibres occur when the amount of specific edge load (SEL) and specific energy (SEC) are changed. Increasing intensity promotes fibre shortening, and increasing specific energy increases fibre swelling especially at an early stage of SEC input (Stone, Scallan and Abrahamson 1968, Paper III). The specific edge load theory is a widely applied method for controlling low-consistency refiners developed by Wultch and Flucher (1958), Brecht, Anthanassoulas and Siewert (1965), and Brecht and Sievert (1966). However, when the refiner control parameters are kept at the same level but refining is carried out with different devices, the refining result may vary significantly (Stephansen 1964, McCaw 1999). For example, fibre shortening may vary and different types of refiner may need to be loaded to different extents to achieve a desired change in fibres. The reason for this is poorly understood. More developed control methods to adjust refiner performance have been introduced later. For example, the C-factor theory was developed by Kerekes (1990). It describes the refiner's ability to inflict impacts on fibres. The so-called specific surface load theory considers the effect of varied bar width (Lumiainen 1990). Despite the progress in developing a better method for refiner control, practical mill floor control methods employ the SEL theory, possibly because it is simple and easy to comprehend. The lack of quickly measurable response variables indicating changes in fibres may be one important reason for the inexact adjustment of refiners.

Consequently, if we aim to achieve a specific amount of structural changes for a certain pulp, our ability to understand and control the refiner so that the desired changed will be achieved is limited. This may be the reason for the wide range of doctrines concerning the operation of low-consistency refiners. For example, experts occasionally recommend one general refining intensity of 2.0 J/m for softwood refining. The author of the present study regarded this type of approach as an oversimplification of refining, which may lead to underutilisation of the potential inherent in the wood fibres. Instead, before this study, the author assumed that different pulps should rather be treated more as a unique material, and that there is room for optimising the performance of the refining process. The demand for more information on refining parameters, fibre changes and correspondent refiner gap behaviour is expected to increase in the future after more reliable on-line measurements detecting structural changes in fibres have been developed.

The problems described above formed the background for this thesis. Thus, the overall aim of this study was to determine specific ways to improve the performance of low-consistency refining. For experimental laboratory work, an LR 40 laboratory refiner was purchased to treat fibres under controlled circumstances. The first aim of the study included analysis of its reproducibility with a view to fulfil the high demands set for scientific experiments. In addition, this model of laboratory refiner had not been used previously in university laboratories.

When determining the scope of the research, the vast literature on refining studies formed a challenge but also an opportunity. First, to select suitable work areas, the refining zone was schematically "divided" into two phases: 1. a liquid phase, with the pulp suspension containing flocculating fibres and 2. a solid phase, with a filling configuration consisting of bars and grooves. These two phases were divided into sub-variables. From these two areas one variable was selected for further study. Their background is described in the following.

The "liquid phase" pulp suspension and its flocculation have been found to play an important role in low-consistency refining (Page et al. 1962, Hietanen and Ebeling 1990, McKenzie and Prosser 1981). Flocculation has been reported to affect the gap between bar surfaces (Hietanen 1991). The magnitude of the gap has been found to affect the extent of structural changes in fibres. A narrow gap often results in more severe changes; for example fibre shortening will be intensified. Ultimately, it is the gap that is adjusted when the load of the refiner is changed. It was assumed that these phenomena acting together need to be understood in more detail. This provided an aim for the second part of the study. However, studying changes in the refiner load and gap and the resultant structural changes is challenging because if another type of pulp is adopted, as done by Levlin (1980), the change in wood species will also cause changes in several fibre properties, such as fibre length, cell wall thickness and structure, and the type and content hemicellulose, which will affect for example the magnitude of the gap and fibre flocculation. To overcome variations caused by different wood species, fractionation of long-fibre softwood pulp with a pressure screen and a hydrocyclone was selected as a way to attain pulp suspensions which differ in terms of fibre length or cell wall thickness but which still contain fibres of the same softwood species as the original pulp. The softwood pulp fractions obtained in this way were refined at different loads and energy inputs, because only a limited amount of information was available on how varied refining intensity will affect fibre properties of fibre fractions. In addition, the gap behaviour was of special interest, so an effort was made to link it to corresponding fibre changes and compression behaviour of fibre flocs reported in the literature (Martinez and Kerekes 1994, Martinez et al. 1997, Senger 1998, Senger and Ouellet 2002)

The aim of the third part of the study was to gain a better understanding of the differences in refining result between the disc and conical configuration and of the bar leading edge sharpness and its effect on the shortening of long softwood fibres. Also, a method was developed to acquire new numerical information on bar edge sharpness. The effect of bar edges on fibre shortening was recognised one hundred years ago (Beadle 1908), but recently its importance seems to have been forgotten, probably because refining is seldom designed to produce fibre cutting. In addition, too rounded bar edges have been reported to reduce the energy efficiency of refining (Sievert and Selder 1976). Consequently, this type of information was assumed to provide guidelines for how to avoid fibre cutting and improve the performance of low-consistency refining of long softwood fibres.

REPRODUCIBILITY AND CONTROLLABILITY

Challenges related to reproducibility

The experimental device, the LR 40 laboratory refiner, is designed to imitate mill-scale refining treatment as closely as possible. Refiner fillings with a pattern similar to that used in a mill refiner can be installed into its frame. With aid of a process logic controller (PLC) the magnitude of the gap, the target intensity and specific energy can be accurately adjusted and monitored. In addition, the instrumentation helps to collect data on the position of the stator, total power calculated from the torque sensor value and inlet pressure. The basic operating principle of the refiner has been described by Sepke, Pott and Melzer (1991) and by Wultch and Flucher (1958). When compared against a mill refiner, the biggest different is the smaller diameter of the refining zone and the fact that the pulp passes the refining zone multiple times, which may affect the heterogeneity of refining.

This type of refiner has mainly been used to compare commercial pulps and to determine suitable intensity and specific energy for mill refining of a specific pulp. However, experimental devices used for scientific study are expected to behave in a reproducible manner. Experiments should be performed with devices which allow them to be reproduced, a demand that led us to study in detail the reproducibility of the LR 40 laboratory refiner's performance after its commissioning in May 2002. Experiments led us to study a detailed procedure for determining the no-load power of the laboratory refiner. The background of the problem related to the no-load power estimate is presented in the following chapters.

Ultimately, a low-consistency refiner is controlled by adjusting the gap between the refiner fillings. The gap is filled with stock suspension that resists the movement of the rotor. Simultaneously, forces are applied to fibres or fibre flocs between the bars, thereby developing structural changes in the fibres. On the other hand, changes in the fibres lead to changes in the nature of the suspension. The behaviour of the suspension, such as the flow pattern and compression of flocs in the refining zone, is poorly understood, which makes control efforts complicated. The complexity is further increased by the fact that the response of the fibres to the disc movement cannot be measured on-line. The overall effect of a decrease in the gap is that the resistance increases and power uptake of the refiner motor increases. However, the power does not increase linearly as a function of the gap (Sferrazza 1985), which further adds to the challenge of controlling the refining process. Moreover, different types of pulp behave in different ways; they form different gap widths (Hietanen 1991) and they flocculate to different degrees (Kerekes et al. 1985). As a result, controlling an LC refiner cannot be compared e.g. to controlling a valve that has a relatively linear response, depending on the valve's position (Sferrazza 1985).

The most widely applied refining control method is the SEL theory. In reality, the net specific energy target is often set, and, depending on the flow of pulp, the SEL is allowed to vary over an acceptable range. In the SEL theory, the set point for the effective power, P_e is determined from the selected intensity level and from the calculated cutting speed, L_s of the refiner fillings. Equation 1 describes the calculation. Here, the effective power that is actually treating the fibres is important because it is a measure of the power amount causing permanent changes in fibres. However, P_e cannot be directly measured and used as a control parameter. Instead, its value is estimated by calculating the power uptake of the motor from voltage and current measurements, or, more rarely, as e.g. in the LR 40 laboratory refiner, by measuring the total power from the refiner's shaft with a torque sensor. The latter way excludes power losses of the electric motor, thus improving the accuracy of total power measurement because the efficiency of an electric motor is never 100%. From the above, the total power, P_t is obtained. From P_t the so-called no-load power estimate, P_{n-l} is subtracted, and the rest represents the effective power treating the fibres, as Equation 2 illustrates.

$$P_e = SEL \times L_s \qquad (1)$$

where P_e estimated effective refining power treating fibres (kW)
SEL specific edge load (J/m)
L_s cutting speed (km/s)

$$P_e = P_t - P_{n-l} \qquad (2)$$

where P_e estimated effective refining power treating fibres (kW)
P_t total measured refining power (kW)
P_{n-l} estimated no-load power (kW)

The “inefficient” no-load power, P_{n-l} contains several sub-components. Power is wasted in fluid acceleration from the inlet zone to the outer radius of the refining zone, fluid hydrodynamics that does not create permanent changes in fibres, and in creating a pressure difference, i.e. the pumping effect of the refiner. Mechanical friction of shaft bearings consumes part of the applied power. Despite several serious efforts throughout the history of refining and beating research, researchers have not succeeded in constructing a comprehensive formula for the division of the different power components (Pfarr 1907, Kirchner 1918, Smith 1923, Dalzell 1961, Banks 1967, Dietemann and Roux 2005). Consequently, in modern paper mills only a very rough procedure for estimating the no-load power is used.

There are several ways to estimate no-load power and how often it is done depends on the mill’s or the laboratory’s interests. Either water or pulp may be used and the magnitude of the gap during the measurement may vary. Often, the estimation is done only once after commissioning of the refiner. Here, two aspects appear important. First, knowing the proportion of no-load power of total power is relevant. If the proportion is large, a possible increase in it causes the effective power to diminish to a higher extent, unless the respective total power set point is increased. This case applies for most laboratory refiners. For example in the LR 40 type laboratory refiner, a decrease in refining intensity leads to an increase in the proportion of no-load power of the total power.

Second, it is important to know how much and how quickly the no-load power will change over a longer time period. Some reports on industrial refining examine this aspect. As any mechanical device, the low-consistency refiner has moving parts which will wear through usage. This will change the level of no-load power (Baker 2003 and McCaw 1999). The change can be tens of per cent. According to Siewert and Selder (1976), wear of the bar height decreases the no-load power linearly. In mill refining, where bar height wear ultimately leads to a change of fillings, this needs to be considered, but in refining pure chemical pulp at laboratory scale the bar height wear is very small and appears to be less significant.

It was concluded that the lack of precision in estimating the no-load power may be one important reason for the reported poor comparability of the refining result. That and the demands set for scientific experiments lead to planning of experiments which aimed at tracking the potential source of variability in laboratory refining. Especially, determining a correct procedure for no-load power estimation was of primary interest.

Results

Short-term variability

After starting the refiner from cold state the total power uptake was high, as illustrated in Figure 1. When the refiner started to warm up, the power uptake decreased relatively rapidly, and then levelled off to form a more linear line. The no-load power measurement included two sequences of 600 s, which were repeated in succession. The set point for the warm-up time also determined the time for pulp circulation before gap closure and the start of the refining sequence. The intension was to keep that time fixed, because changing it would change the pulp mixing time.

During the last 600 s run, the power curve decreased only slowly, approaching steady state. Corresponding temperature measurements from the surface of bearing casings indicated that the bearing temperatures reached a steady state after about 1800 s. The actual bearing temperature inside the casing could not be measured.

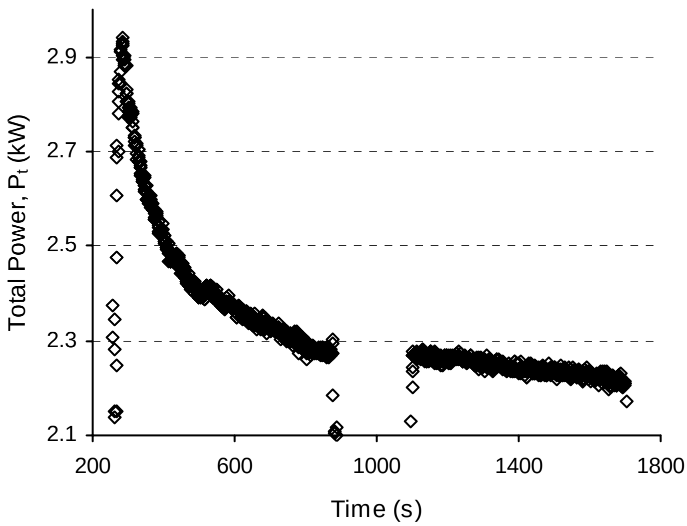

Figure 1. Power uptake after refiner start. Two 600 s measurement sequences were applied.

The no-load power of the laboratory refiner was intentionally varied by decreasing the warm-up time; correspondent warm-up time values were; 1200 s, 300 s, 100 s. Already a 12 % increase in no-load power was found to have a significant effect on the refining of HWK at low 0.3 J/m intensity. The calculated statistics (P-values) indicated that warm-up time, significantly affected mean values of SR, apparent density and light scattering coefficient. Calculated statistics are presented in Table 5 in Paper I. The largest effect is caused by the shortest warm-up time of 100 s and when specific energy was high 100 kWh/t. This increased the no-load power from 2.29 to 2.56 kW (12 % increase from 100 s to 300 s), and the SR increased from 45 to 54. Among the selected response variables, the effect of “incorrectly” estimated no-load power on light scattering is illustrated in Figure 2. A similar effect was in seen in the apparent density. In laboratory refining at 0.3 J/m intensity, the proportion of no-load power of total power varied in the range 72-75 %.

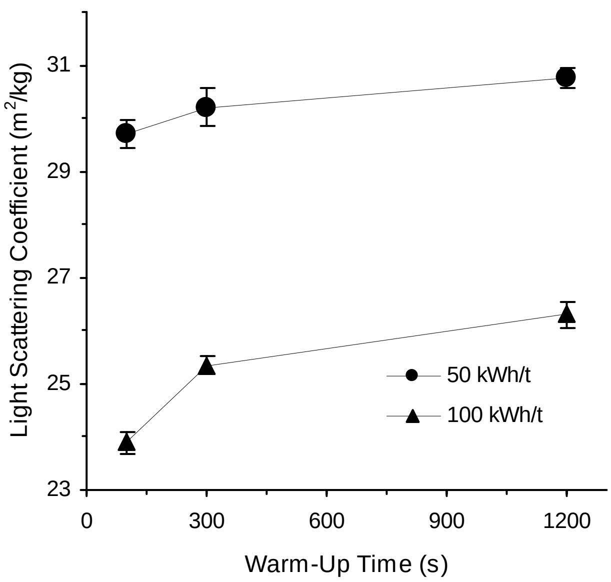

Figure 2. Light scattering coefficient versus warm-up time .

Long-term variability

After commissioning, the laboratory refiner showed a marked decrease in estimated no-load power. Most of the no-load values from 2002 were recorded once after 300 s warm-up time using water and a gap of 1mm. This procedure was recommended by the supplier of device. Some individual values, however, were recorded after two times 300 s. This may cause slight variability in the results measured before August 13, 2002. Anyway, after a few months' operation of the laboratory refiner, no-load power dropped by about 15 %. Lubricating the bearings with fresh grease decreased the no-load power only slightly.

Discussion

The results indicated that accurate estimation of the no-load power is important for a modern laboratory refiner. The refiner needs to warm up and be close to steady state before recording the no-load power. The no-load power needs to be checked regularly because its level may change over a longer time period due to adaptation of moving parts and mechanical wear. Adaptation of parts can be expected to occur especially after the commissioning of the refiner. The role of no-load power is more important in laboratory refining, where its proportion of total power is high. Depending on the refining intensity, it may represent over 50 % of total power.

Whether the results can be directly applied to industrial refiners should be tested with full-scale experiments. Anyway, some recommendations can be given. If the no-load power of a mill refiner has been determined only once after commissioning, the level of no-load power has probably changed, so the actual calculated effective power and specific energy will deviate from the more realistic values. Bar height wear changes the no-load power, but if the change is linear as a function of time, as reported by Siewert and Selder (1976), its effect could be modelled by analysing the relationship between time, bar height wear and recorded no-load power.

At present, the no-load value has a fixed value in the control algorithm of paper mill refiner, but by taking into account the above effects of mechanical wear of moving parts and bar height wear, through regular checking a more realistic value could be achieved for the no-load power and for the effective power treating the fibres. For example, later in this study it is shown that the swelling of fibres follows specific energy. Accordingly, if we want to control swelling and internal fibrillation, an accurate value is needed for specific energy. To achieve this, we need to detect the changes in the no-load power of the refiner.

To this end, regular checking of no-load power is recommended. For a laboratory refiner, a daily estimation before experimental runs is recommended. Before recording the value the refiner needs to warm up.

REFINING SOFTWOOD KRAFT FIBRE FRACTIONS

Introduction

There are a number of methods for selecting fibres with suitable dimensions. One way is selecting the right kind of chips in the wood yard. In fractionation, the original pulp can be divided to two different classes. The fractionation is mainly based on fibre dimensions. Accordingly, if a pressure screen is used to fractionate softwood fibres, the accept and reject are primarily classified in terms of fibre length (Scott and Abubakr 1994, Olson et al. 1998). If a hydrocyclone fractionator is used, the fibres are classified more according to their cell wall thickness (CWT) (Paavilainen 1993). The driving force behind fractionation of chemical pulp fibres is the need for more suitable fibres for a specific paper grade or layer of board. However, knowledge of the optimum way to refine softwood fibre fractions was found to be limited. There are reports on the refining of different fractions, but when selecting refining parameters such as refining intensity, the fractions have been treated as normal softwood pulp (Paavilainen (1993) Vomhoff and Grundström 2003), assuming that the fractions behave as the original pulp. The potential for optimising the refining intensity and its effect on fibre properties had not been examined in those studies. Having acquired preliminary information indicating that some fibre fractions may not tolerate the high refining intensity which can be applied to normal Scandinavian softwood pulp, the author of the present study decided to conduct refining studies in which maximum refining intensity was mapped for a specific fraction and wide range of refining intensities and specific energy levels were applied in treating the fractions. In addition, the magnitude of the gap during refining was monitored.

The refining study of softwood fractions comprised three parts. Preliminary information indicated that the load-carrying capacity of the short-fibre fraction (SF) produced by a pressure screen fractionator may be reduced. Therefore, the maximum load-carrying capacity of pressure-screen fractions was mapped first. Because the amount of fractionated pulp was limited, the mapping was executed in 0.5 J/m steps. The accepted maximum intensity was one step downwards from the intensity at which the motor load of the refiner started fluctuating.

Second, among the structural changes in fibres, fibre shortening, fibre swelling and the fibre pore size structure were of special interest. A wide range of refining intensities and specific energy levels were applied to fractions after the maximum load-carrying capacity had been mapped. It was studied how the control parameters affected structural changes in fibres and handsheet properties. This was assumed to provide future guidelines for refining of softwood fractions.

Third, an effort was made to link the flocculation tendency of the fractions and the refining intensity to the magnitude of the gap. To describe fibre flocculation numerically, the crowding factor (N) of the pulps was calculated based on Equation 3, put forward by Kerekes and Schell (1992). To describe the fibre flocculation numerically for pulp fibre suspensions it is often convenient to use mass consistency, C_m, fibre length, L, and fibre coarseness, ω, to compute N. C_m is expressed in %, L in m and ω in kg/m. N was calculated both for unrefined fractions and for refined test points.

$$N \approx \frac{5C_m L^2}{\omega} \qquad (3)$$

Published literature suggests that fibre flocculation and gap phenomena are interlinked. Watson and Phillips (1964) showed how eucalypt and radiata sulphate pulps produced different gap widths when refined in a PFI mill. The overall effect of beating appears to be breaking down the flocs of fibres (Page, Kosky and Booth 1962). Hietanen and Ebeling (1990) have suggested that flocculation is the reason for heterogeneous refining. Flocculation has been reported to affect the gap between bar surfaces (Hietanen 1991). McKenzie and Prosser (1981) suggested that the design of the refining system should take into account the initial stage of the pulp, and how it is affected by the refining process, in other words, whether the pulp is initially present as large flocs or whether its flocculating ability is significantly affected by the refining operation. The next chapters present the main findings of experiments in which

SWK pulp fractions where refined. The detailed discussion on the mechanism behind the gap behaviour of the fibre fractions is reported in Paper III.

Maximum load-carrying capacity of specific fibre fractions

Before the actual refining series, the maximum intensity for the fractions was mapped. Because the amount of fractionated pulp was limited, the mapping was executed in 0.5 J/m steps. The accepted maximum intensity was one step downwards from the intensity at which the motor load of the refiner started fluctuating. The maximum load-carrying capacity of the short-fibre fraction was different from that of the original pulp and the long-fibre fraction. The short-fibre fraction tolerated a maximum intensity of 2.4 J/m, whereas the feed pulp and long-fibre fraction tolerated an intensity of 3.7 J/m. Based on the above, the maximum intensity-carrying capacity of the short-fibre fraction was close to the "universal" intensity of 2.0 J/m often recommended for softwood refining. Hydrocyclone fractions tolerated the highest applied intensity of 3.7 J/m without problems. Measured fibre properties of unrefined pulp fractions, i.e. average fibre length and cell wall thickness (CWT), are illustrated in Appendices 1 and 2 of Paper III.

Fibre shortening and fibre swelling

The critical refining intensity which enhanced fibre shortening was significantly lower for the short-fibre fraction. An intensity of 2.4 J/m shortened the fibres of the short-fibre fraction (SF) increasingly, while the other fractions showed only mild shortening at this intensity. Figure 3 illustrates the decrease in average fibre length of pressure-screen fractions when specific edge load and specific energy were varied.

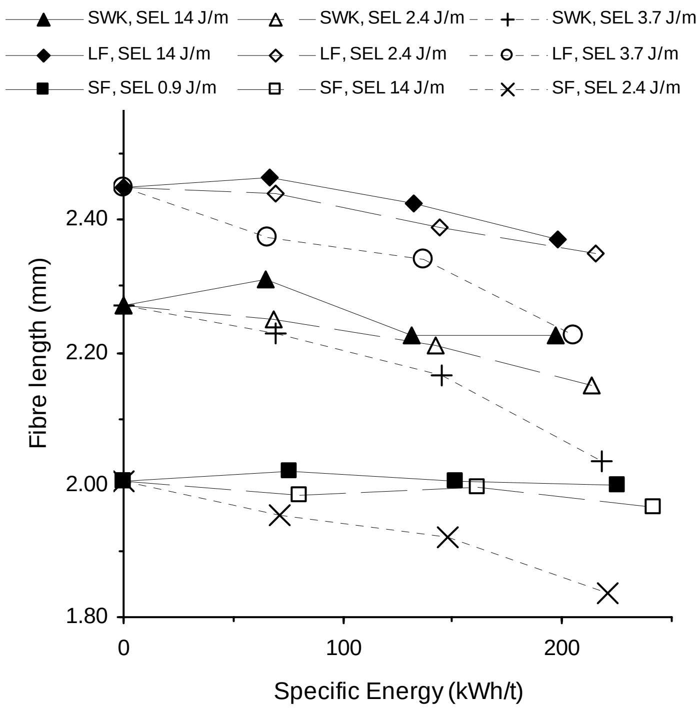

Figure 3. Fibre shortening of softwood kraft pressure-screen fractions.

In addition, at a given intensity, the gap of the short-fibre fraction was narrower than the gap of the original pulp (SWK) or the long-fibre fraction (LF). According to Hietanen (1991) increased intensity decreases the gap, which increases the susceptibility to fibre cutting. The above results fit the proposed fibre failure mechanism due to tensile-type stress; at a narrow gap, the fibres are effectively pinched between other fibres and one end of the fibre may be held by the bar edge, from which follows that fibres are strained by tensile-type stress (Page 1989, Kerekes and Senger 2006). Based on the above, the intensity promoting shortening was fraction-specific, since at 2.4 J/m intensity the short-fibre fraction was increasingly shortened. This finding suggests strongly that optimisation needs to be done when fractions are refined.

Specific energy proved to be the parameter explaining the fibre swelling of all fractions. At the beginning of refining, at a low specific energy, the fibre saturation point (FSP) value increased most, and later, when more specific energy was applied, the slope of the curve decreased slightly. Figure 4 shows the FSP versus specific energy for the all fractions refined at different intensities. Interestingly, neither the type of fraction nor the refining intensity affected the swelling of fibres. In a swollen cell wall, the size of the smallest pores opened by refining was approximately 50 µm, as indicated by thermoporosimetry measurement. In a study by Stone et al. (1968) the swelling of kraft fibres was reported to increase at the beginning of refining, then levelling off.

Fibre swelling was important for the development of sheet density and tensile strength. On the other hand, specific energy is a combination of the number of impacts and their intensity (Leider and Nissan 1977, Kerekes et al 1993). In view of this, increased swelling and tensile strength are achieved most energy-efficiently at the highest possible intensity and with a low number of impacts. However, increased refining intensity may be detrimental to fibre length, which impairs strength. For the mechanical treatment made in a low-consistency refiner with symmetric bars and grooves the dilemma remains whether the number of impacts could be increased energy-efficiently. Increasing peripheral speed would be a theoretical option, but in this case the no-load power would increase too.

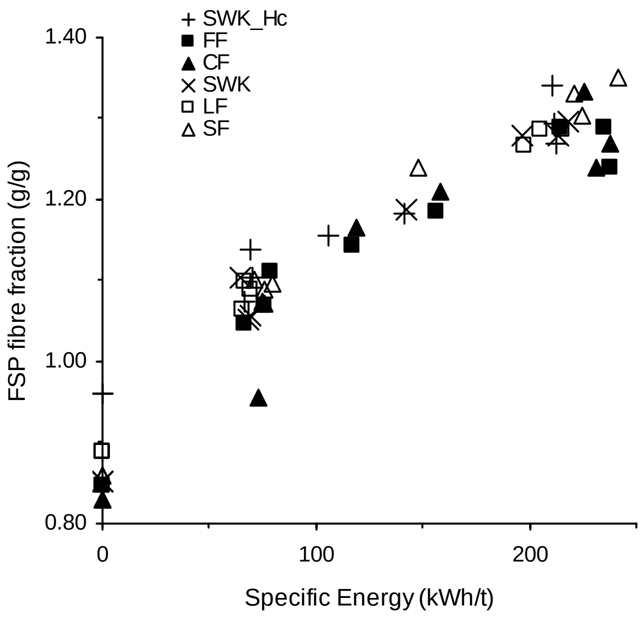

Figure 4. Fibre saturation point (FSP) of all the fractions refined at different intensities. FSP measured from fibres which contained no fines.

Magnitude of gap

Effect of intensity on the gap

Figure 5 illustrates the magnitude of the gap for pressure-screen fractions. At intensities of 1.4 J/m and 2.4 J/m, the gap of the short-fibre fraction was significantly smaller than the gap of the other two fractions. The difference in gap was approximately 50 µm when compared against the original pulp at an intensity of 2.4 J/m and the corresponding difference compared to the long-fibre fraction was 86 µm.

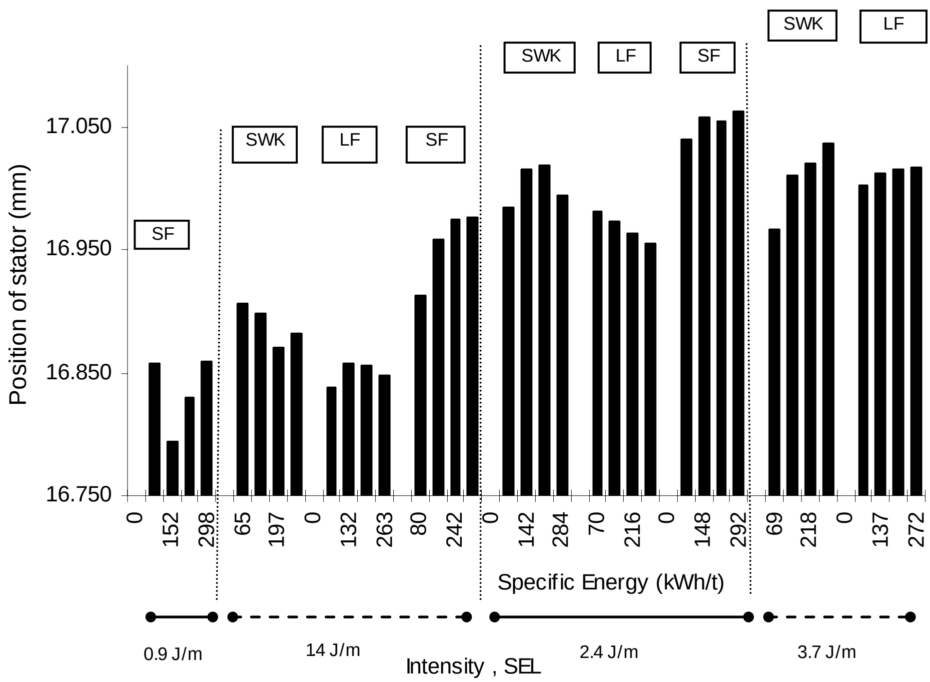

Figure 5. Magnitude of gap (indicated by the movement of stator) for pressure-screen fractions under varying refining intensity and specific energy. The higher the value of the y-axis, the narrower the gap.

The pressure screen fractions differed mainly in terms of fibre length and less in terms of coarseness and CWT (Appendices 1 and 2 of Paper III). When the calculated crowding factor (N) was plotted against the magnitude of the gap, the short-fibre fraction reached a narrower gap range where also the crowding factor was lowest. Also visual assessment of short-fibre pulp suggested a lower tendency to flocculate. Figure 6 shows the crowding factor versus the magnitude of the gap. Though the crowding factor is not designed for the circumstances prevailing in a low-consistency refiner, it might serve as a first indicator of the risk of reduced load-carrying capacity and fibre shortening and be applied in cases where the type of pulp type is changed to a pulp with different fibre length.

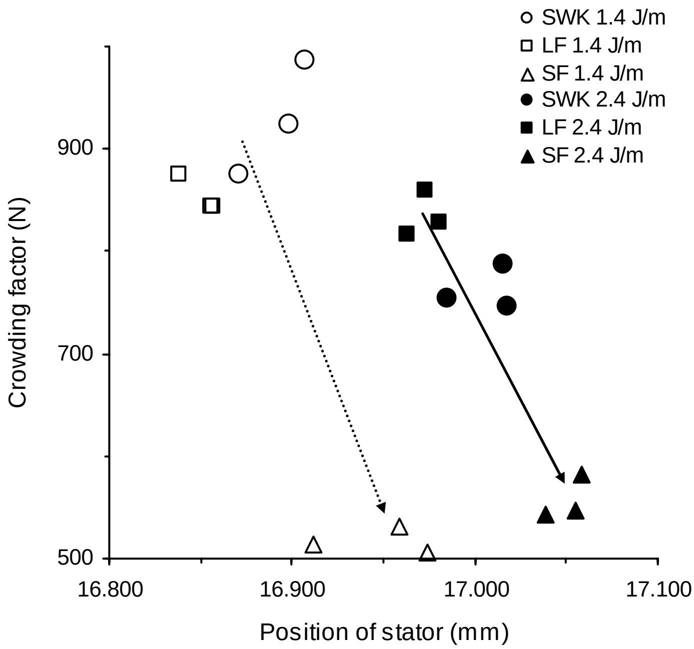

Figure 6. Crowding factor as an indicator of the magnitude of the gap.

Effect of specific energy on the gap

The overall effect of specific energy on the magnitude of the gap was smaller than that of variations cased by the intensity. The effects of intensity and specific energy on the gap were interconnected, so that increased specific energy caused the gap to decrease at high and medium intensity refining of a specific fraction, but not at the lowest intensity of a specific fraction. At the lowest intensity of the fraction, the change in gap due to specific energy was unsystematic.

For the short-fibre fraction the “low” intensity where the gap was not decreased systematically by increased specific energy corresponded to an intensity of 0.9 J/m. For the hydrocyclone fractions similar behaviour was seen at an intensity of 1.4 J/m. The gap of the long-fibre fraction did not decrease systematically at 1.4 and 2.4 J/m intensity, but at a high intensity of 3.7 J/m it did. A reduction in the gap due to increased specific energy has been reported by several researchers (Lundin 2003, Watson et al. 1962, Watson et al. 1966, Murphy 1962, Range 1951, Watson and F.H. Phillips 1964). From the above, we can conclude that the commonly recognized gap decrease after the pulp has been refined further (to higher SEC) occurs mainly at medium and high intensity of specific pulp. In such a situation, cell wall thickness and cell wall flexibility and compression may have an important role in determining the magnitude of the gap.

It should be noted that the consistency of the pressure screen fractions varied due to pulper leakage, which made interpretation of the gap results more uncertain. The gap behaviour in refining is discussed in more detail in Paper III of this thesis and the complexity related to consistency in Paper II. In summary, the gap behaviour of a low-consistency refiner appears to be a complicated phenomenon affected by several suspension, fibre and filling parameters. Among these, floc compression and fibre lumen and cell wall compression between the bar surfaces, the ability of flocs to tolerate stress applied by bar surfaces, and the ease of floc entrance between the bars (heterogeneity) have an important role.

Summary

The maximum refining intensity which could be applied to the short-fibre fraction of a typical Scandinavian softwood pulp was found to be lower than the maximum intensity of the original pulp and long-fibre fraction. In addition, the fibre shortening of the short-fibre fraction became more severe already at 2.4 J/m intensity. In a way, the behaviour of the short-fibre fraction during refining was moving towards the behaviour of hardwood pulp, which needs to be refined at clearly lower intensity and which forms a clearly narrower gap than softwood pulps. This result emphasizes the importance of optimising the refining of softwood fractions. Especially, the refining intensity should be carefully mapped. Internal fibrillation mainly followed specific energy and was not dependent on intensity, the type of fraction or the gap. Internal fibrillation increased the apparent density and tensile strength of the handsheets.

Applying the crowding factor as a preliminary indicator of the magnitude of the gap was tested and it showed interesting results. Despite its limitations if applied to refining, it might be tested for example for softwood kraft pulps in a situation where the raw material and especially average fibre length of pulp is changed. In such cases it might indicate an increased risk of reduced load-carrying capacity leading to “pad collapse” and a risk of fibre shortening.

IMPACT OF REFINER CONFIGURATION AND BAR EDGE PROFILE ON FIBRE SHORTENING AND REFINER GAP

Introduction

Disc and conical refiners are the most common low-consistency refiner configurations in mill-scale refining. The operating principle is the same for both: pulp is fed from the inlet of the refiner through the refining zone to the outlet pipe. Several sub-types of both configurations can be found, depending on whether there are one or two stator elements on the side of the rotating element. Consequently, one or two refining zones can be formed. Both types are believed to produce approximately the same refining result, and they can be controlled by the same control methods, e.g. by adjusting the specific edge load and specific energy. However, comparing disc and conical refiners under well controlled process circumstances is difficult. Thus, there are relative few reports on comparisons between these two devices.

Certain differences exist, however. In the conical configuration the cone angle may vary. The centrifugal force in the conical configuration is directed more towards the grooves of the stationary cone (Banks 1967, Goncharov 1980). In a disc refiner, the centrifugal force is directed more in the direction of the primary flow in the grooves. This may change the flow pattern in filling grooves, but the exact effect is not understood in detail. Consequently, the heterogeneity of refining may vary, but its magnitude is an open question. In practice, the possible difference in heterogeneity seems less significant, because the overall efficiency of refining is low. It has been reported that 1-10 % of the energy used in LC refining will create internal fibrillation (Kerekes and Senger 2006). Van Den Akker (1961) evaluated the energy needed in an ideal refining process for loosening the internal structure of the fibre, producing fibre cutting and creating microscopic fuzz in the fibre surface (some type of external fibrillation). He concluded that “a tremendous gap exists between the level of energy now expended in beating and refining and that which would be consumed in a nearly ideal process”. Based on the above, the overall efficiency of LC refining seems to be low, but apparently there is no real efficiency difference between different refiner models. If such a difference existed, the poorly performing configuration would most probably have vanished from the market.

Besides the refiner configuration, the so-called filling macrostructure also affects the refining result. The scale of the macrostructure is measured in several millimetres (Stephansen 1964). Among these parameters, the bar and the groove width and the depth can have different dimensions, and the bar intersecting angle may vary. The effect of macroparameters on the refining result is relatively well described in the literature (Brecht et al. 1965, Nordman et al. 1980, Lumiainen 1995, Melzer and Siewert 1995, Bergfeld 1999). On the other hand, the so-called filling microstructure has a more diffuse role in affecting the refining. Its dimensions can be measured in tens of micrometers (Stephansen (1964). For example the filling roughness falls into this category. Muller-Ried et al. (1965) and Lundin and Lönnberg (2004) have studied the effects of different filling materials, finding marked differences in pulp properties. Lundin showed that an abrasive filling causes severe fibre shortening also in chemical pulps, but no roughness values were reported. Syrjänen (1965) pointed out that the filling surface should not be too smooth. From the past we know that basalt lava fillings and filling surfaces treated with ammonia (Stephansen 1964) cause changes in refining, but the mechanism has not been reported in detail.

Among the parameters of the filling microstructure, the bar leading edge sharpness, or more accurately the bar edge form profile, was selected for further study. The latter term is used in literature of surface geometry. Analysis of bar edge form profile was selected because measured numerical information could not be found on it, and because bar edge sharpness has been reported to cause fibre shortening (Beadle 1908, Smith 1951, Cotrall 1965), affecting refiner efficiency and the refining result (Sievert and Selder 1976, Banks 1967). Recently, Baker (2003) has reported that different material compositions affect the edge and bar height wear and consequently the geometry of the bar edge profile changes. The bar edge wear and bar height wear are interconnected (Baker 2003, Sievert and Selder 1976). If the leading edge profile retains a sharper profile, its height decreases faster, and conversely a harder material resists more bar height wear, which leads to a rounder shape of the leading edge profile. This will affect the durability of the filling.

The aim of this part of the study was to gain a better understanding of the differences in refining result between the disc and conical configuration, as it was possible to install both of them in the LR 40 laboratory refiner. Fibre shortening and the strength properties of handsheets made from softwood and hardwood pulps were analysed as indications of the refining result. Also, a new method was developed to acquire numerical information on bar edge sharpness. Since the bar edge sharpness of disc and conical fillings was found to vary, its effect was tested by artificially modifying edges of disc fillings and treating the same softwood kraft pulp. Here, the fibre shortening of long-fibre softwood pulp was of special interest.

Results and discussion

Impact of refiner configuration on fibre shortening and handsheet properties

Both configurations were used to refine softwood and hardwood kraft pulp. The disc fillings produced clearly stronger fibre shortening, especially when SWK was refined. The shortening was severe already at 2.8 J/m intensity, as illustrated in Figure. 7, and it intensified further when refining intensity was increased to 4.0 J/m. For HWK, the disc fillings caused somewhat stronger shortening at both intensities applied: 0.5 J/m and 1.5 J/m, as illustrated in Figure 8.

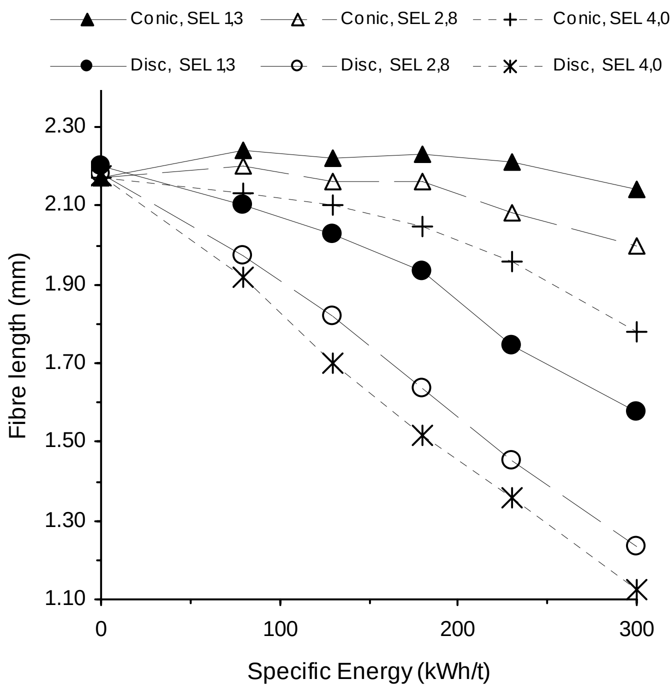

Figure 7. Effect of refining intensity and refiner configuration on shortening of SWK fibres.

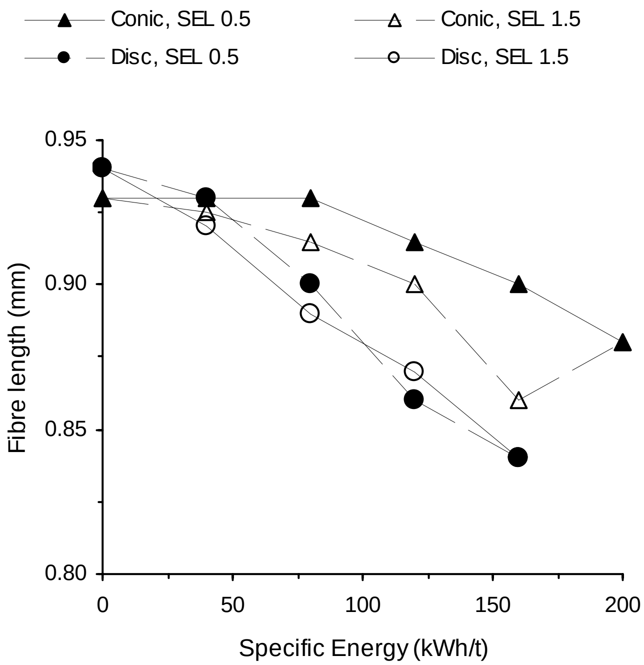

Figure 8. Effect of refining intensity and refiner configuration on shortening of HWK fibres.

Among handsheet properties, the tensile strength of HWK improved with an increase in handsheet density. This is illustrated in Figure 9. Higher final density and tensile strength were achieved at low 0.5 J/m intensity and with both configurations. The tear strength at a given tensile strength of HWK handsheets was more affected by the refining intensity than by the refiner configuration. The tear strength at a given tensile strength of SWK remained at a lower level when the pulp was refined with disc fillings at medium 2.8 J/m and high 4.0 J/m intensity.

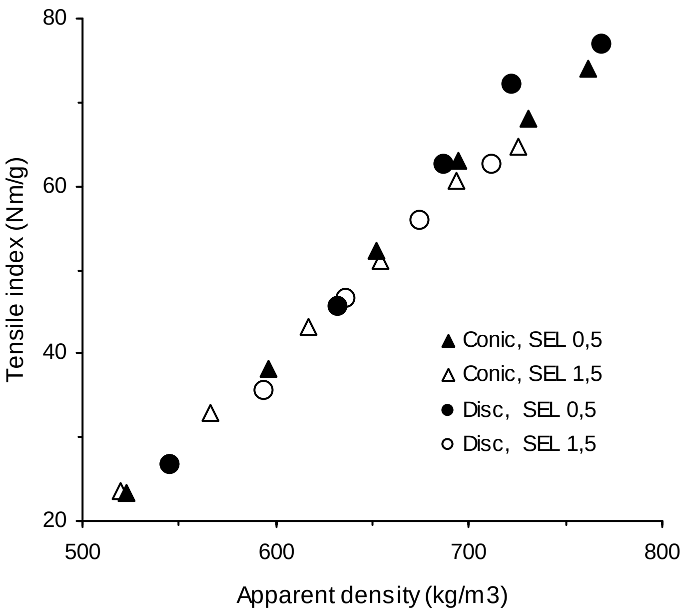

Figure 9. Tensile strength versus apparent density of HWK.

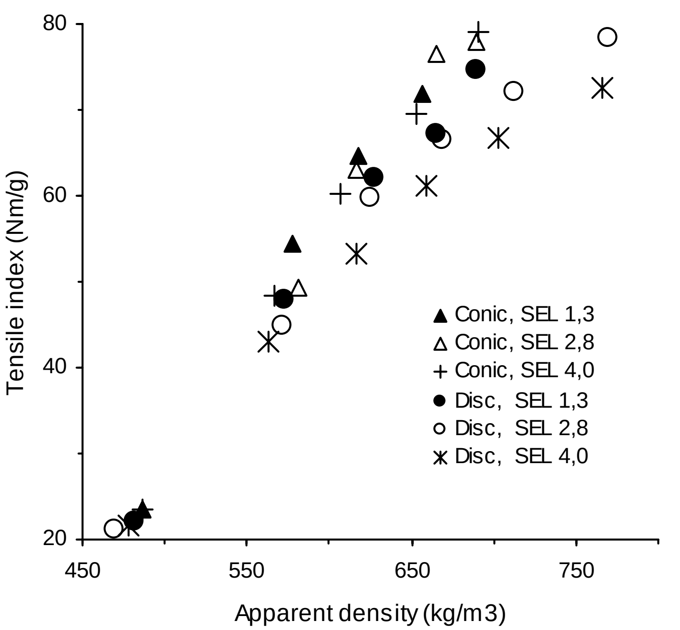

Figure 10. Tensile strength versus apparent density of SWK.

Oppositely to HWK pulp, the tensile strength at a given density of SWK handsheets decreased when using disc fillings and higher 2.8 - 4.0 J/m intensities, as illustrated in Figure 10. At the same time, fibre length was strongly reduced, which indicates that disc fillings produced harsher conditions in the refining of softwood fibres. In such harsh conditions, other types of fibre damage may have arisen, leading to weak spots in fibres and the handsheet fibre network, thereby impairing tensile strength. However, such damage could not be detected from the measurements used. Mohlin and Miller (1995) concluded that the improvement in tensile-WRV relationship is probably due to fibre straightening when the shortening of fibres remains moderate. Their experiments were conducted at a low intensity of 1-2 J/m in pilot-scale conical and disc refiners. In Levlin's (1980) experiments, pine kraft pulp started to display severe fibre shortening when refining intensity was increased from 2.0 to 4.0 J/m. In our study, the lower bonding ability of fibres could have been one reason for the deteriorating tensile strength of SWK handsheets, but measured fibre swelling and Scott-Bond values indicated good bonding for SWK refined at 2.8 J/m and with disc fillings.

Based on the above, the increase in tensile strength under milder refining conditions and with both configurations seems to depend on fibre swelling and the consequent increase in density of handsheets. If refining becomes harsher, as found when refining SWK with disc fillings and at medium and high intensity, the risk of deteriorating tensile strength increases. Here, the long-fibre softwood kraft was found to be a sensitive fibre raw material, and in a situation where severe fibre shortening occurs the tensile strength also deteriorates. Hardwood pulp did not show a similar dependence on the filling configuration.

The gap values of softwood refining indicated that with disc fillings a "minimum gap" was reached already at 2.8 J/m intensity, since an increase in intensity up to 4.0 J/m did not close the gap much further. On the other hand, the gap of conical fillings decreased further at increased intensity, which indicates that the overall gap was wider for conical fillings. From this follows that there must have been more material between the bars of conical fillings. The reason for this phenomenon is hard to conclude, but the wider grooves of conical fillings which expand towards the outer refining zone may have helped to disperse flocculating fibres more effectively. Smith (1923) proposed that wider grooves create more turbulence or that pulp is rotating more readily in wider grooves. Whether the difference in the direction of centrifugal force between the conical and disc configuration changes the flow so that more fibres are captured in the gap of conical bars remains an unanswered question.

At one stage, the author of this study thought that rounder bar edges might help fibre flocs to enter between bar surfaces, as pointed out in Paper IV. Therefore, the effect of bar edges on magnitude of gap was further studied, but with disc fillings which were easier to machine.

Bar edge form profile and fibre shortening

The method developed for measuring and calculating numerical values for bar edge form profile is described in Papers IV and V. Using this method, new numerical information on bar edge profiles was obtained. The results of the bar edge profile modification indicated that the risk of severe fibre shortening increased when the "sharp" leading bar edge profile had a radius of leading edge curvature smaller than about 30-50 µm, or if the profile contained small-scale flaws such as scratches that may occur after casting and finishing of fillings. As shown in Figure 11, sharp edges caused severe shortening at a given refining intensity, while the blunt edges retained the fibre length relatively well. The leading edge of the "sharp" stator had a small radius of curvature (34 µm). In addition, the leading edges of the "sharp" rotor contained several small-scale angular-form edges (n=6). Both of these are assumed to hold fibres so strongly that fibre failure by tensile stress will follow. As pointed out by Kerekes (2006), sharp edges may act as an effective point of restraint of fibres, and the other end of the fibre can be pinched between other fibres of the compressed fibre floc.

The published literature contains few reports on the effect of bar edge rounding on refiner loadability and on the magnitude of the corner force created by the bar edge. Frazier (1988) examined the effect of wear of the bar edge profile and the bar height on the performance of a mechanical pulp refiner. He summarised that the relationship of "thrust", P, and "load", L, increases when the bar edge becomes rounder and bar height decreases. In the equations proposed by Frazier, P illustrates pressure and L is used as a symbol for shear force. On the basis of the equation, Frazier apparently suggests that in high-consistency refining bar wear increases the need to load the refiner more, while simultaneously the proportion of the normal force of the shear force increases. In practical mill refining, it can be seen that when bar wear proceeds, the refiner needs to be loaded more until eventually the refiner motor's loadability reaches its limit, whereas the development of fibre properties remains moderate. Consequently, fillings need to be changed. However, it has not been widely reported that especially fibre shortening is promoted during the above-mentioned "wear phase". It seems clear that the calculated pressure on the fibre mat between bars shall increase in cases where bar edge wear is strong because the loaded bar-crossing area decreases. Whether the fibre mat's thickness increases simultaneously with strong bar wear cannot be confirmed, but it is possible due to lower groove depth, and rounder bar leading edges, which lead to a higher lift component if considered as a body immersed in a suspension.

Roux (2001) has proposed that fibre shortening in low-consistency refining may depend on over-pressure on the fibre mat between the bar surfaces. Batchelor et al. (1997) formulated an equation for the corner force acting on individual fibres in low-consistency refining. The proposed corner force equation includes a component for bar leading edge radius. After inserting values into the equation (Eq. 10, Batchelor et al 1997), the smaller value of bar edge radius leads to a higher corner force acting on an individual fibre. In studying shear-forces in high consistency refining, Senger and Oullet (2002) suggested that the bar edge radius determines how much the bar edge digs into the fibre floc. A sharper bar edge will dig deeper into the floc, will act as a stress concentration point and will result in a strong corner force. The earlier observations of fibre shortening caused by sharp edges, the studies by Batchelor et al. (1997) and Senger and Oullet (2002) and the results of the present study would all seem to support the conclusion that the more severe fibre shortening by sharp edges at a given refiner intensity can be explained by the previously mentioned mechanism of fibre pinching and tensile-type fibre failure.

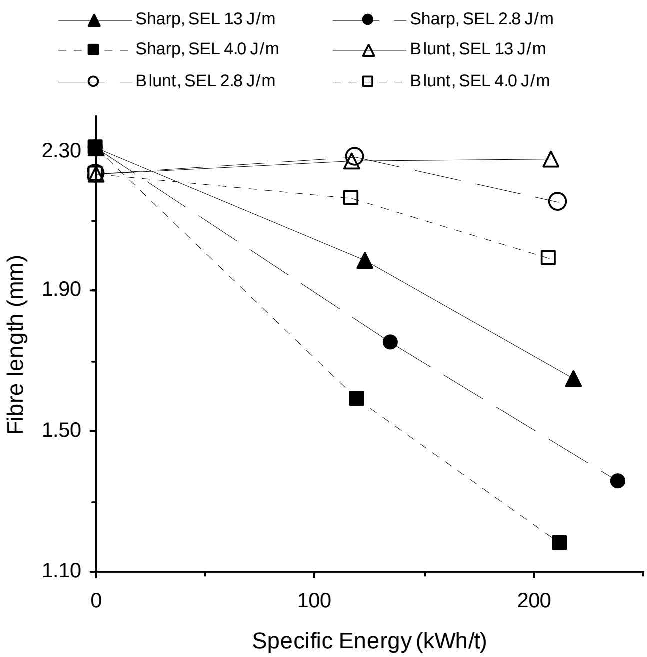

Figure 11. Fibre shortening caused by sharp and blunt disc filling edges at different refining intensities and at different levels of specific energy.

In summary, the results showed that the condition of bar leading edge remains an important parameter also for a modern LC refiner. To optimise fibre shortening and energy efficiency, the filling material should be selected with care. Bar edge wear which keeps the radius of the leading edge curvature in the range of 80 – 150 µm would seem to represent an optimum for Nordic softwood kraft pulp, as in this case fibre shortening is still moderate. Additional bar edge rounding may reduce the energy efficiency of refining (Siewert and Selder 1976).

Magnitude of gap

The relative stator movement indicating the magnitude of the gap was recorded by PLC from the measured position of the stator. For conical fillings, the cone angle was noted in gap calculations, as illustrated in Equation 4, where R is the measured stator movement of the conical stator and R_C is the calculated relative movement of the stator. In summary, the magnitude of the gap depended on the type of pulp, refining intensity, pulp consistency and the refiner configuration. The effect of these parameters on the gap is discussed in the following chapters.

$$R_c = \sin 30° \times R \quad (4)$$

Effect of pulp type and configuration on gap

As expected, the type of pulp affected the gap, with softwood showing larger changes in the gap than hardwood. The narrower overall gap in hardwood pulp refining has been reported by several researchers (Watson et al. 1966, Watson and Phillips 1964, Murphy 1962 and Watson et al. 1962). Levlin (1980) reported that the gap in refining birch kraft is approximately half the gap in refining pine kraft, which may be due to the lower flocculation of hardwood fibres or dimensional differences in the cell wall. Hardwood and softwood fibres differ in several respects: their fibre length, cell wall thickness, stiffness and chemistry, type of hemicellulose, cell wall structure, fibril angle and types of cell are all different (Levlin 1980). The number of fibres per gram of pulp-water suspension is also higher for HW pulps.

The results showed that an increase in intensity caused a decrease in the gap, but the magnitude of the decrease was quite different for HWK and SWK. When the intensity in refining SWK was increased from 1.3 J/m to 4.0 J/m, the gap decreased by more than 150 µm, and with both configurations. Figure 12 illustrates the gap in softwood refining with both configurations. With disc fillings at high intensities of 2.8 and 4.0 J/m, the minimum gap before "pad collapse" was achieved, since the gap could not decrease further. With conical fillings the gap of SWK decreased more linearly with increased intensity. This was interpreted to mean that more fibre flocs may have entered between the bar surfaces of conical fillings. As already discussed in the Results section concerning the effect of the filling configuration, it was not possible to determine the actual mechanism causing the difference in gap behaviour between disc and conical configurations when increasing intensity to the highest level of 4.0 J/m. When the bar edges of discs were modified, no significant diffrences in the gap magnitude occured. Whether the range of bar edge radius had some effect here can only be speculated. Alltogether, bar edge radius of disc fillings ranged over smaller values than those of conical fillings.

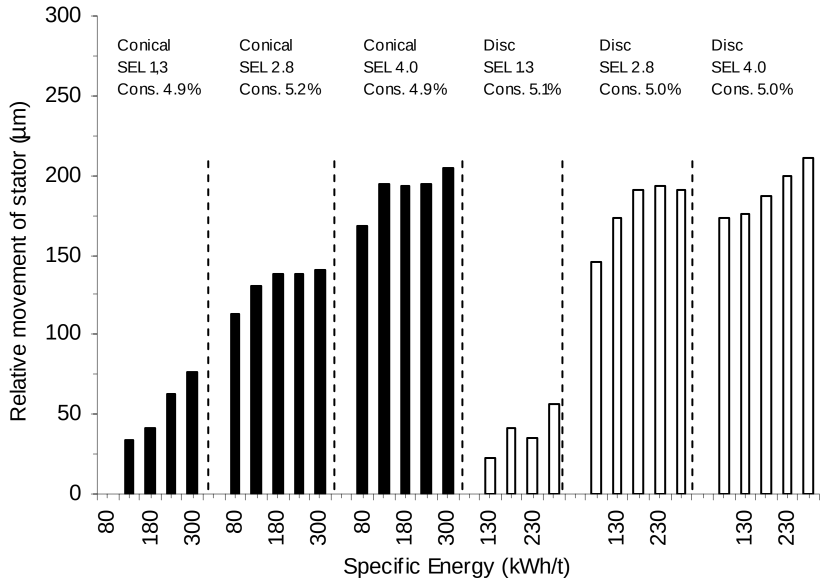

Figure 12. Magnitude of gap for softwood pulp refined with disc and conical fillings.

The gap in HWK refining behaved differently from that in SWK refining. An increase in intensity from 0.5 J/m to 1.5 J/m did not cause a systematic change in the magnitude of the gap. However, an increase in specific energy caused the gap to decrease over the range of 25-35 μm with both configurations. Surprisingly, the decreasing effect on the gap caused by increased specific energy and with conical fillings was seen only at low 0.5 J/m intensity, but with disc fillings the SEC effect was seen at high 1.5 J/m intensity. These gap results were slightly confusing and could not be explained. The controller of the refiner can adjust the gap in steps of 1 μm, and the controller seemed to function properly. No overshooting in control actions was noticed. The PLC records the stator position just before sampling. Recording a momentary data value may not be the best possible way to collect data. Later, the possibility to record the whole stator position sequence during refining has been introduced by installing add-in software in the computer of the LR 40 laboratory refiner, which makes it possible to calculate for example a mean value for the sequence between the sampling.

Discussion on gap behaviour of hardwood versus softwood refining

As described in the previous chapter, the refining intensity caused the gap to behave differently, depending on the type of pulp. With hardwood, the range of variation was smaller. This may be due to the smaller floc size of hardwood fibres, as proposed by Levlin (1980), or the lower floc network strength of hardwood fibres. A shorter fibre will coil less around neighbouring fibres and is hooked to a smaller extent by other fibres, thus forming a weaker network. In such a case, shear forces generated by passing bars will probably cause the hardwood fibre floc to break more easily into smaller ones than a floc formed by softwood fibres.

Another possible reason causing the hardwood gap to vary less may be how evenly fibres are spread in the gap. The fact that an increase in intensity did not systematically decrease the gap with hardwood fibres may indicate that hardwood fibres are spread relatively evenly, independent of refining intensity. In such a case, the increased stress on fibres caused by increased intensity would concentrate on deforming the lumen structure and cell walls of separate fibres and shearing the fibre surface, not the floc structure. Whether the amount of hardwood fibres between bars is affected by the refining intensity has not been reported. Those images captured from refining zone have been taken from softwood pulp refining. According to Page et al. (1962), a decrease in refining intensity to a "brushing value" when beating spruce sulphite pulp in an Aylesford conical refiner immediately produced a larger number of fibres and fibre flocs in the beating zone.
From the above it can be concluded that at least for softwood fibres the change in intensity is also a selection process determining the number of flocs entering

between the bars. From this follows that at higher intensity fewer flocs are stressed and strained more severely and compressed into smaller dimensions, and eventually the fibre lumen and cell wall are compressed into small volumes. This could explain the measured large change in the magnitude of the gap of softwood pulps.

Finally, the above discussion would seem to suggest that the floc structure and control of its deformation and transmission of forces via neighbouring fibres are more important in low-consistency refining of softwood fibres. In the refining of hardwood fibres, adjacent fibres may play a smaller role, and structural changes in fibres are created more by transmitting forces via fibre-metal interaction in a narrow gap. Then, for example the bar surface roughness could have more importance in the development of structural changes of hardwood fibres. Further studies in this area are recommended. To highlight the open question regarding the heterogeneity of hardwood and softwood refining and how fibres are located in the treatment zone, sharp images should be captured of the refining zone.

Effect of pulp consistency on gap

The “refiner configuration” experiments included test points where pulp consistency was varied. In refining HWK the effect of consistency variations was tested only with the conical configuration. Increasing the consistency of HWK from 3 to 4 %, the gap was closed by some tens of micrometers. An increase in specific energy did not change the gap systematically.

In refining SWK the effect of consistency variations was tested with both the disc and conical configuration. The consistency of SWK was varied in the range of 3-5 %. The configuration had a prominent effect on the magnitude of the gap. When consistency was raised from 4.1 % to 5.0 % the gap narrowed by 59 µm with disc fillings, whereas with conical fillings the gap widened by 19 µm when consistency was raised from 4.1 to 5.2 %. In a study by Lundin (2003) using a conical laboratory refiner, a similar increase in the consistency of SWK pulp was found to widen the gap by about 70 µm. Watson and Phillips (1964), Watson et al. (1962), Watson et al. (1966) and Murphy (1962) have reported increased gap widths due to increased consistency in experiments with a PFI mill. When consistency was increased from 5 to 10 %, the gap increased, but the largest gap variations were caused by different wood species (Radiata versus Eucalyptus).

It should be noted that the effect of specific energy on the magnitude of the gap was logical in all points where SWK consistency was varied, except at low 1.3 J/m intensity with disc fillings. When more specific energy was applied, the gap of both configurations decreased, as is often seen in chemical pulp refining. Moreover, the average fibre length of SWK was again more severely reduced by disc fillings and the reduction was strongest at higher 4-5 % consistency, in a situation where the gap became narrower. With conical fillings fibre length was reduced slightly more at low 3 % consistency than at higher consistencies. As earlier, the conical fillings produced more moderate fibre shortening. From the above it appears that the refiner configuration together with pulp consistency affect the magnitude of the gap.

Effect of bar edge profile on gap

The finding that conical fillings had a rounder bar leading edge than disc fillings focused the author’s attention on the role of the bar edge profile in promoting the entrance of fibre flocs between bar surfaces. This aspect was examined by studying literature on flow over immersed bodies where lower drag and higher lift coefficients are reported for rounder bodies immersed into a flowing fluid (Fox and McDonald 1994). This approach has a clear analogy to an earlier published schematic example of filling bar edge ploughing where a rounder-edged toboggan digs less into snow than a sharp-edged one (Senger and Oullet (2002). Hence, the gap variation was analysed from the experiments in which the bar edges of disc fillings were artificially modified. At 2.8 J/m intensity the gap of discs having “sharp” edges was narrower than with “blunt” edges, but unfortunately the consistency was also lower due to pulper leakage during the slushing of pulp. The average radius of the leading edge curvature of sharp stator bars was 34 µm; for blunt stator leading edges the corresponding value was 80 µm. Thus, at least over the tested range of leading bar edge sharpness, the leading edges having a rounder shape did not seem to cause more effective entrance of fibre flocs into the gap.

Summary of gap behaviour

The following parameters affect the magnitude of the gap: 1) type of pulp, in other words whether the refined fibres originate from hardwood or softwood, 2) refining intensity, 3) pulp consistency, 4) specific energy and 5) refiner configuration by some mechanism. In general, the type of pulp had the strongest effect on the magnitude of the gap, with the variation in the refiner gap being much larger with softwood than with hardwood when intensity was changed. This result is in line with earlier reports of gap changes, in which the type of pulp was found to cause the largest change in the gap (Watson and Phillips (1964), Watson et al. (1962), Watson et al. (1966) and Murphy (1962).

With softwood pulp, increased refining intensity caused the gap to decrease by a few hundreds of micrometers, but with hardwood pulp no systematic gap decrease could be detected. Both of these effects are believed to be related to the compression of fibre flocs and fibres and to how evenly fibres are spread in the gap. For softwood, the floc structure and impact of neighbouring fibres appears to be important, whereas for hardwood the compression of a single fibre's lumen and cell wall structure may have a larger role in determining the gap. These areas should be studied further, because eventually it is the gap that is controlled in low-consistency refining. Changes in pulp consistency caused the gap to vary in surprising ways, so its effect with different configurations and over a wider range of filling bar edge sharpness should be studied in more detail.

CONCLUSIONS

The aim of this study was to explore specific methods to improve the performance of low-consistency refining. The experimental work focused on the following areas: 1. analysis of the reproducibility of the laboratory refiner, 2. refining of softwood fibre fractions, 3. examining the role of the effect of the refiner configuration on fibre and handsheet properties and the effect of the bar edge profile in causing shortening of long softwood fibres.

Accurate and regular determination of no-load power was found to be important for achieving a reproducible refining result. In laboratory refining the device must be allowed a sufficient warm-up time before the no-load power estimate is recorded. In laboratory-scale conditions the estimation should be made daily before experiments. For the LR40 laboratory refiner used in the present experiments a warm-up time of 1200 s was found to be sufficient.

In low-intensity refining, where the proportion of no-load power is high, applying a precise procedure for no-load power estimation is particularly important. In addition to short-term variability, the LR 40 laboratory refiner's no-load power varied over a longer time period. This was probably due to adaptation of moving parts and some mechanical wear after the commissioning of the refiner. In paper mill conditions, the no-load power is typically estimated only after commissioning of the refiner or occasionally after that, depending on the mill's interests. This may lead to less accurate estimates of effective power and net specific energy, if no-load power has changed and is not corrected into the control algorithm. This may be one reason for the poor comparability of refining results from different refiners. Therefore, more attention should be paid to regular estimation of the no-load power of mill refiners. Modelling the effect of bar height wear on the no-load power should also be studied in the future to develop a control algorithm that detects the effect of bar height wear on no-load power.

The results of refining experiments with fractionated softwood pulp support the view that softwood pulp refining needs to be carefully optimised. Especially optimum refining intensity should be mapped, because the fractions may have reduced load-carrying capacity. In addition, for the short-fibre fraction more severe fibre shortening starts at lower intensity than for the original pulp or long-fibre fraction. Refining intensity together with the type of fraction was found to have a strong effect on the magnitude of the gap, with the short-fibre fraction forming a narrower gap at a given intensity than the original pulp or long-fibre fraction. The fraction's specific intensity and the gap are believed to be linked to fibre flocculation and compression of flocs between bar surfaces. More studies in this area are recommended to gain a better understanding of the fundamentals of gap phenomena.

Profilometer measurement combined with a new method for calculating the bar edge form profile supplied new numerical information on bar edge sharpness. An effort was made to link it with measured softwood fibre shortening. Sharp bar edges and bar edges containing smaller-scale flaws caused the most severe fibre shortening. To avoid severe fibre shortening of long softwood fibres and to retain the efficiency of refining at a high level, the composition of filling materials together with the wear properties of the leading bar edges should be considered in more detail than has been done so far. For Scandinavian softwood kraft pulp a bar edge radius larger than approximately 80 micrometers appeared to reduce the risk of severe fibre shortening. If the edge becomes much rounder, the energy efficiency of refining may decrease, as reported by Siewert and Selder (1976). Further studies are proposed to gain more numerical information on the edge wear of different filling materials. The amount of filler in the pulp to be refined and the pH of the suspension probably have some importance for the development of edge wear, so their effect should not be forgotten.

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