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Final thesis

Factors Affecting the Axial Force in Low-Consistency Refining

Supervisor Licentiate in Technology, Päivi Viitaharju
Commissioned by Metso, supervised by the Global Product Manager of the Valkeakoski Service Center, Markku Partanen

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ABSTRACT

This work is based on the empirical research of axial force in low-consistency refining. The purpose was to identify factors affecting the axial force by refining trials. Similar research has been carried out in the past by Metso, where the refiner fillings effect on axial force was compared. Trials have shown that wear of the refiner fillings raises the axial force. This has been attributed to reduced volume between the bars which results in fibres and fibre flocs get harsher treatment. Axial force contributes to the refining result and the serviceable life of refiner parts so an extensive research into the axial force was needed.

Through literature review and from previous experience the influencing factors of axial force were listed. The axial force was estimated using the results from fibre suspension, geometry of fillings and rotor motion. The impacts of these factors were measured by the conical refiner trials where four different kinds of cone-shaped fillings were used. Refiner fillings were rotated in both directions using three refining energy levels. The effects of rotation speed, production level and wear of the fillings on axial force were examined with one filling. Samples of pulp were taken from 17 test points and by analysing them the energy level, refiner fillings and direction of rotation impact on paper strength properties were examined.

Refiner trials indicated that the axial force grows when rotation speed decreases or production level increases. A lower rotation speed and a higher production level needs a smaller gap clearance to achieve the same *SRE*. A reduction in gap clearance produced higher axial forces. Force caused by pressure difference decreases the axial force, so smaller axial forces were measured when fillings were rotated in the pumping direction. A tilted bar staples more fibres on the bar edge in the attack direction, which increase the gap clearance but the axial force grows. Wear of the bar edges and dense fillings increased the axial force. A straight and a tilted bar treated the fibres quite equally. A rounded bar edge cut the fibres and the paper strength properties were significantly reduced.

More information of the force in the refining zone is needed. In addition, a tilted bar might achieve a longer fillings life time which should be tested on a mill scale. These results could be used in fillings development.

Confidential

Keywords	axial force, low-consistency refining, geometry of fillings

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TIIVISTELMÄ

Tämä työ perustuu matalasakeusjauhatuksen aksiaalivoiman kokeelliseen tutkimukseen, jonka tavoitteena oli löytää aksiaalivoimaan vaikuttavat tekijät. Metsolla on aikaisemmin tehty vastaavia kokeita, joissa on vertailtu terien vaikutusta aksiaalivoimaan. Nämä tutkimukset osoittivat terien kulumisen ja aksiaalivoiman riippuvuuden: kun terät ja särmät kuluvat, niin aksiaalivoima kasvaa. Tämän on katsottu johtuvan pienentyneestä terävälin tilavuudesta, jolloin kuidut ja flokit saavat voimakkaamman käsittelyn. Aksiaalivoima vaikuttaa jauhatustuloksen lisäksi jauhimen osien kestävyyteen, joten kattavampi aksiaalivoiman tutkimus oli tarpeellinen.

Aikaisempien kokeiden ja kirjallisuuden avulla määritettiin aksiaalivoimaan vaikuttavat tekijät. Aksiaalivoiman arvioitiin johtuvan kuitususpensiosta, terien geometriasta ja roottorin liikkeestä. Näiden tekijöiden vaikutusta mitattiin koeajolla, jossa käytettiin neljää erilaista kartiojauhimen jauhinterää. Jauhinteriä pyöritettiin molempiin suuntiin kolmella energiatasolla. Yhdellä terällä selvitettiin pyörimisnopeuden, tuotantotason ja terien kulumisen vaikutus aksiaalivoimaan. Massanäytteet otettiin 17 mittapisteestä, joiden avulla tutkittiin pyörimissuunnan, terän ja energiatason vaikutusta valmistettavan paperin lujuusominaisuuksiin.

Koeajot osoittivat aksiaalivoiman kasvavan, kun pyörimisnopeus pienenee tai kun tuotanto kasvaa. Alhaisempi pyörimisnopeus ja korkeampi tuotanto vaatii pienemmän terävälin saavuttaakseen saman *EOK*:n. Terävälin pienentymisen huomattiin kasvattavan aksiaalivoimaa. Paine-eron tuottama voima pienentää aksiaalivoimaa, joten pumppaavaan pyörimissuuntaan pyöritettäessä mitattiin pienempiä aksiaalivoimia. Kallistettu terä tuottaa suurempia aksiaalivoimia molempiin pyörimissuuntiin. Kallistettu terä pinoaa enemmän kuituja hyökkäävään suuntaan, mikä aiheutaa suuremman terävälin, mutta kuitenkin suuremmat aksiaalivoimat. Teräsärmien pyöristyminen ja tiheät terät nostavat aksiaalivoimaa rajusti. Paperin lujuusominaisuuksissa ei havaittu merkittäviä eroja kallistetun ja normaalin terän välillä. Särmän pyöristyminen katkoi kuituja voimakkaasti, mikä johti lujuusominaisuuksien romahtamiseen.

Seuraavaksi voitaisiin tutkia voiman kehittymistä terävälissä. Lisäksi kallistettu terä saavuttanee pidemmän teräiän, mitä voitaisiin tutkia tehdaskoeajolla. Tuloksia voidaan käyttää jauhinterien kehityksessä.

Luottamuksellinen

Avainsanat aksiaalivoima, matalasakeusjauhatus, terägeometria

Foreword

Axial force was found to be very influential in low-consistency refining. More information about refining was elicited. These results could not have been achieved without the great team we had.

I would like to thank everyone involved in this research at FTC. Especially, Sari Härmä-Kallio and Riitta Tuominen who helped me with the hand sheet study. Jorma Halla and Håkan Sjöström gave lots of ideas about what we should find out from the axial force.

It has always been easy to work with you Päivi. I am most indebted to Markku Partanen for his advice.

Finally, I have Anni to thank for taking care of our family.

Valkeakoski June 2010

Marko Loijas

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List of symbols

FTC	Fiber Technology Center
ISO	International standards organization
LF	Long fibre fine-type fillings
LC	low-consistency
NBKP	Northern Bleached Kraft Pulp
SC	Short fibre coarse-type fillings
SCK	Short fibre coarse tilted-type fillings
SEL	Specific Edge Load, J/m
SSL	Specific Surface Load, J/m^2
SR	Schopper-Riegler, °SR
SRE	Specific refining energy, kWh/t
ULFK	Unifibre long fibre tilted-type fillings

1 Introduction

Paper and board products consist of many different components such as wood fibres, water and chemicals. Wood fibres are the basic raw materials of paper. Fibres are separated from wood either chemically or mechanically. These fibres have a poor bonding ability so they are refined with a mechanical stress between refiner bars. This process opens the fibres causing increased bonding surface area and flexibility of fibres. As a result the strength properties of paper are improved. (VTT Industrial systems 2009)

However, the modification of fibres needs lots of energy and energy consumption raises papermaking costs. The axial force effectively transposes force to loading force which interacts with fibres in the refiner. When axial force increases, the energy consumption of the refiner increases as well. So it is very important to know about factors affecting the axial force.

1.1 Aim of study

The aim of this work is to examine the impact of different factors affecting the axial force in low-consistency refining. Initially, a study was conducted of results gained in earlier trials where axial force was investigated. Secondly, constructions of low-consistency refiners were considered. In addition, refining theories were investigated and on the other hand effects of refining on paper properties were analysed. On the basis of these, factors affecting the axial force in low-consistency refining were listed. Finally, the effects of process parameters and refiner fillings on the axial force were tested with low-consistency refining trials at the Metso Fiber Technology Center in Anjalankoski. The effect of two different kinds of refiner fillings on paper strength properties were compared at the same time.

1.2 Previous research into the axial force at Metso

Measurements of the axial force have been done for decades in Metso. Axial force measurements have been a part of other research but extensive research concerning the effect of different factors on axial force in low-consistency refining has not been done. However, loading devices have broken from refiners and this is thought to be a result of too high axial force. (Partanen, 2010)

The comparison of new and used fillings has shown a correlation between wear of the fillings and the axial force; when the refiner fillings wear down the axial force increases. This is supposed to be a result of less space for the fibres and fibre flocs between the fillings. In particular, this phenomenon has occurred with the fine fillings. In addition, when the power requirement of the refiner rises the axial force grows in relation to the power-law rate equation. (Partanen, 2010)

Axial force measurements were undertaken with two fillings in 2007. The flank angle with the old fillings was 20° and with new fillings the angle was less. This trial showed that the axial force of new fillings was about 10 % less than the older model. (Miettinen 2007, 37) A few years' later the vibration of fillings was analyzed with three fillings. In addition, the axial force was measured, when a pressure difference relating to the axial force was noticed. Moreover, the direction of rotation and rotation speed seemed to have an effect on axial force. The variation in the force was affected by the rotation direction. The highest axial force was measured with fillings where the stator filling had more bars compared to the rotor filling and those bars were tilted. (Miettinen & Nuutila 2009, 2; 40; 42)

2 Theory

The theory part presents a literature review of the main factors concerning the pulp refining and the occurring axial force. By dint of refiner construction, refining theories and effects of refining on paper properties the factors affecting the axial force in low-consistency refining were figured out. Even so, this part concentrates on the conical refiner.

2.1 Low-consistency refiner construction

The first batchwise operating refining machine, called Hollander beater, has developed into continuously operating conical, cylindrical and disc refiners (Figure 1). The target of all these machines is to modify fibres so they can create a continuous, strong and desired network of fibres. The mechanical energy is transferred to fibres in a suitable consistency when the desired properties of paper or board are achieved. (Lumiainen 2000, 87-101)

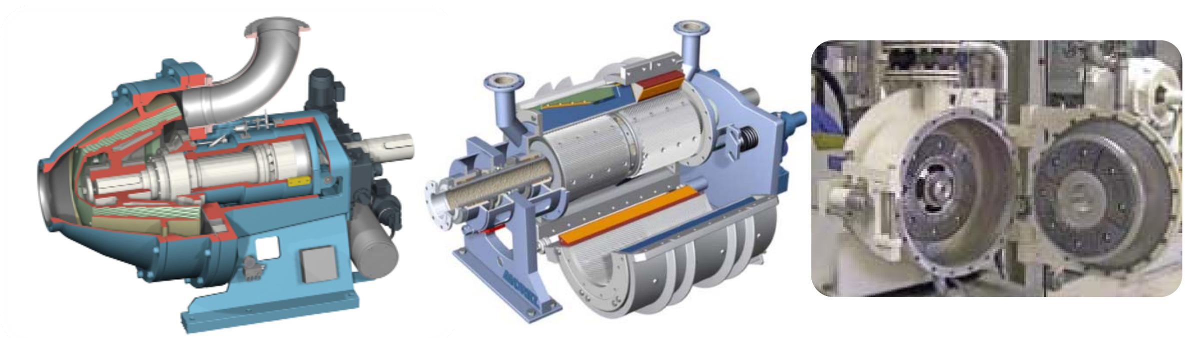
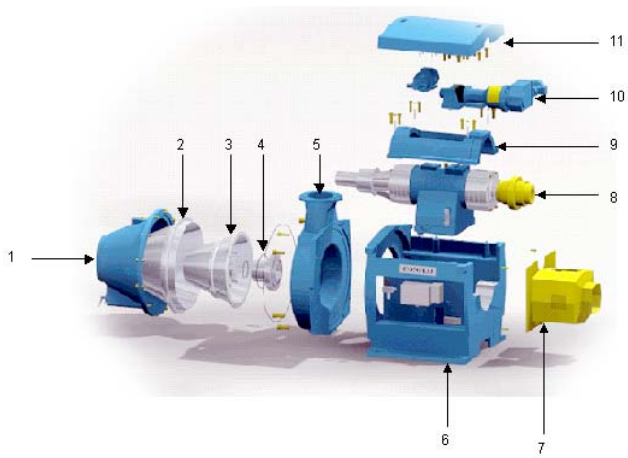


Figure 1: OptiFiner™ conical refiner (left) (Metso 2008b), Papillon™ cylindrical refiner (middle) (VTT Industrial systems 2009), TwinFlo™ TF.E disc refiner (right) (Voith Paper 2010)

All these refiners in figure 1 are designed to operate in low-consistency between 3 – 6 %. Refining consistency depends on fibre length of the feed stock and the desired refining effect. Long fibres have a tendency to form flocs in which case fibres inside the flocs get unequal treatment compared to those that touch the refining bars. The long softwood fibres are refined to a consistency of around 3.5 – 4.5 % and when short hardwood fibres are refined the consistency is about 4.5 – 5.0 %. (Lumiainen 2000, 106; VTT Industrial systems 2009)

A low-consistency refiner is composed of 11 main parts (Figure 2). Pulp is pumped to the refiner through the feed end where the stator filling is attached. The pulp fibres enter between the rotating rotor filling and the stationary stator filling. After the treatment of the refiner bars, pulp exits the refiner through the refining chamber, which is fastened to the frame of the refiner. (Metso 2008b, VTT Industrial systems 2009)



1 = Feed end
2 = Stator fillings
3 = Rotor fillings
4 = Hub
5 = Refining chamber
6 = Frame
7 = Coupling guard
8 = Shaft unit
9 = Bearing housing cover
10 = Loading device
11 = Cover

Figure 2 OptiFiner™ RF Refiner construction (Metso 2008b)

Inside the frame a shaft unit operates which transposes the input electrical energy of the motor to the mechanical rotating force of the rotor and handles different vibrating forces by means of bearings. From one side, the shaft unit is connected to the rotor by the hub and the other side is connected to the motor through the gear coupling. The loading device (attached to the frame and shaft unit) adjusts the position of the shaft unit and consequently the gap clearance of the refiner fillings. (Metso 2008b; Partanen 2010)

2.2 Refining theories

Theories of refining describe the nature and amount of refining. Theories are used to control refining conditions and to evaluate refining. The following theories are used in low-consistency refining with cone- and disc-shaped fillings. (Lumiainen 2000, 91) The creation of refining theories goes back more than a century and the first theory of refining was introduced by Jagenberg in 1887 (Lumiainen 2000, 91)[1]. From those days, many

[1] Original source: Jagenberg, F.1887. Das Holländergeschirr in Briefen an einen Papiermacher

different refining theories have been developed. Even so, this part presents only three most widely used theories.

2.2.1 Specific edge load theory

Specific edge load theory describes the amount and nature of refining by the specific refining energy (*SRE*) and by the specific edge load (*SEL*). This two-parameter characterization of pulp refining was introduced by Brecht and Siewert (1966) who pursued the work of Wultsch and Flucher (1958). (Lumiainen 2000, 92)[2]

In specific edge load theory the *SRE* (or *SEC*)(kWh/t) and the *SEL* (J/m or Ws/m) are

$$SRE = \frac{P_e}{m} = \frac{P_t - P_o}{F \cdot C_s} \tag{1}$$

$$SEL = \frac{P_e}{L_s} = \frac{P_t - P_o}{CL \cdot n} \tag{2}$$

where P_e (kW) denotes net power which is the difference between the total refiner power P_t (kW) and the idling power P_o (kW). Mass flow m (t/h) is the product of volume flow F (m^3/h) and pulp consistency C_s (%). The cutting speed L_s (km/s) is the result of multiplying the cutting length *CL* (or *CEL*)(km/rev) by the rotational speed n (rev/s). (Lumiainen 2000, 93; Koskenhely 2007, 116)[2]

Cutting length *CL* (km/rev) is calculated as

$$CL = z_r \cdot z_s \cdot l \tag{3}$$

where z_r and z_s are the number of rotor and stator bars and l (km) is their average length. (Lundin 2008, 48)[2]

[2] Original source: Brecht, W. & Siewert, W.H. 1966. Das Papier 20(1):4

This theory is widely used because all the factors are easily available and calculations are simple. In any case, many important factors have gone by the board because this theory is based on the assumption that effective refining power is applied to fibres by the edges of the bars. (Lumiainen 2000, 93 - 94)

2.2.2 The specific surface load theory

Lumiainen assumed (1990) that the energy is applied to the fibre flocs from the edges of the bars (*SEL*) as well as during the edge-to-surface phase. So, the impact length of the bars *IL* (m) and the number of refining impacts *IN* (km/kg) had to be included. This theory attained its final form in the middle of 1990. (Lumiainen 2000, 94)[3, 4]

In the specific surface load theory the *SRE* (kJ/kg) is calculated as

$$SRE = IN \cdot SSL \cdot IL \quad (4)$$

where *IN* (km/kg) is the number of refining impacts, *SSL* (J/m^2 or Ws/m^2) is the specific surface load and *IL* (m) is the bar width factor. These three factors are calculated as

$$IN = \frac{L_S}{m} \quad (5)$$

$$SSL = \frac{SEL}{IL} \quad (6)$$

$$IL = \frac{W_r + W_S}{2} \cdot \frac{1}{\cos\left(\frac{\alpha}{2}\right)} \quad (7)$$

where L_s, *m* and *SEL* are calculated according to equations (1), (2) and (3). The impact length *IL* (m) is computable from width of the rotor W_r (m) and stator bars W_s (m) and from the average intersecting angle α (°) of those bars. (Lumianen 2000, 95)

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[3] Original source: Lumiainen J.J. 1990. A new approach to the critical effecting on refining intensity and refining result in low consistency refining. TAPPI 1990 Papermakers Conference Proceedings
[4] Original source: Lumiainen J.J. 1995. Specific surface load theory. PIRA 3rd International Refining Conference Proceedings

The specific surface load theory seems to work when the fibre floc covers the whole width of the bar surface during a refining impact. This theory has partly replaced the specific edge load theory but still the specific surface load theory doesn't observe factors such as the grooves of the fillings and length of fibre. (Lumiainen 2000, 95 – 97)

2.2.3 C-factor

The effective refining energy is considered to be the attribute of the number and nature of the refining impacts. In this way the refining process was characterised for the first time by Lewis and Danforth in 1962. (Lundin 2008, 52)[5] Kerekes (1990) used the same approach as Lewis and Danforth and came to a conclusion that the effective energy E (J/kg) depends on

$$E = N \cdot I = \frac{C}{F} \cdot \frac{P_e}{C} \qquad (8)$$

the number of impacts N (kg^{-1}) and intensity or energy of impact I (J). In this theory the factor F (kg/s) is pulp mass flow and P_e (W) denotes net power which is applied to the refiner. (Lundin 2008, 55)[6] Then Kerekes developed the C-factor which is a combination of filling geometry, rotation speed, consistency, fibre length and coarseness. If bar patterns of rotor and stator are identical and the bar clearance is shorter than the groove depth, the C-factor for a conical refiner is

$$C = \frac{8\pi^2 G D \rho C_f l n^3 \omega (1 + 2\tan\varphi)(R_2^3 - R_1^3)}{3w(l+D)} \qquad (9)$$

where G (m) is width and D (m) is depth of grooves, ρ (kg/m^3) is density of water, C_f (fraction) is pulp consistency, l (m) is length of fibre, n is number of rotor and stator bars on circle in refiner, ω (rev/s) is the rotational speed, φ (°) is bar angle from radius, R_1 is inner

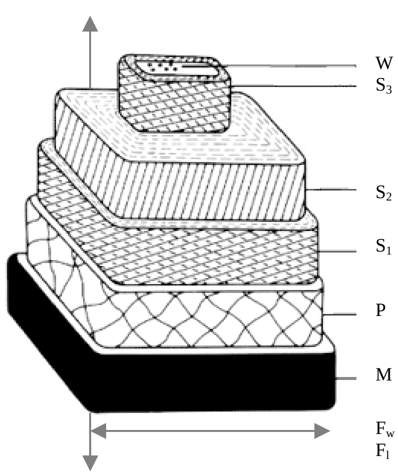
[5] Original source: Lewis, J. & Danforth, D.W. 1962. Stock preparation analysis. Tappi J. 45(3), March 1962, pp 185 – 188
[6] Original source: Kerekes, R.J. 1990. Characterization of pulp refiners by a C-factor. Nord. Pulp Paper Res. J. 16(1):3 - 8

and R_2 (m) is outer radius of the refining zone and *w* (kg/m) is the coarseness of fibre. (Lumiainen 2000, 96 – 97; Lundin 2008, 55 – 56)

The original presentation of the C-factor presented over 30 equations by Kerekes. This part represents only one simplified equation of C-factor where it can be noticed that C-factor theory is detailed but based on specific edge load (*SEL*) and specific surface load (*SSL*) theories anyway. In spite of all, C-factor theory ignores the wear of fillings and some fibre-related issues, e.g. fibre flexibility and the interdependency of fibres. C-factor is a function of various factors and some of those are difficult to determine so this theory is not so much used. (Lumiainen 2000, 96 – 97; Lundin 2008, 55 – 56)

2.3 The effects of refining on paper properties

Wood fibres are the structural material of paper. In order to understand the effects of refining on paper properties the effects of refining on fibres must be clarified. Wood fibre is made up of four parts: (W) tubercular core (lumen), ($S_{1, 2, 3}$) secondary wall, (P) primary wall and (M) intermediate lamella (Figure 3). (VTT Industrial systems 2009)



W = tubercular core

S_3 = secondary wall inner layer (tertiary wall)
S_2 = secondary wall middle layer (P & S thickness 7.5 µm)
S_1 = secondary wall outer layer

P = primary wall (thickness 0.1 µm)

M = intermediate lamella (thickness 0.5 – 1.5 µm)

F_w = fibre width (30 µm)
F_l = fibre length (3 mm)

Figure 3 Structure of Nordic softwood tracheids (VTT Industrial systems 2009)

The chemical composition of these layers is primary cellulose, hemicelluloses and lignin. The cellulose and the hemicelluloses molecules have a way of forming hydrogen bonds with the adjacent molecules. The fibres of paper are interrelated with each other by force of these hydrogen bonds, thus giving the fibre network its strength. The largest amount of cellulose and hemicelluloses is in the secondary wall so the cell wall must be opened. Even as lignin, which does not form bonds easily, the relative amount is the highest in the primary wall and in the intermediate lamella. (VTT Industrial systems 2009) So removal of the primary wall and S_1 layer improves strength properties of paper.

The main effects of refining on fibres are the removal of the primary wall and the S_1 layer, internal and external fibrillation, straightening of fibres (LC refining), delamination and swelling of fibres, creation of fines and shortening of fibres. (VTT Industrial systems 2009) This part analyses the effects of refining on paper properties by utilising refining theories.

2.3.1 General properties

The nature and amount of refining has an effect on fibre properties and this way on the paper properties. Refining is divided into cutting and fibrillating refining. (VTT Industrial systems 2009) Kerekes had the opinion that cutting refining dominates when fibres get few but large impacts. According to C-factor theory (equation 8) the energy of impact, *I*, should be relatively larger than the number of impacts, *N*, and the cutting effect is attained. On the other hand, when the energy of impacts, *I*, is in a minor role the refining is more fibrillating. (Lundin 2008, 53)[6]

Refining increases the density of paper which means that the basis weight of the paper grows and the thickness of the paper decreases.[7] If refining is cutting the effect is stronger. When fibre is cut to little pieces the amount of those pieces could fit in less space. Bulk is the inverse value of density, so bulk is reduced by refining (Figure 4).

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[7] density of sample (kg/m^3) = basis weight of sample (g/m^2) / thickness of sample (µm)

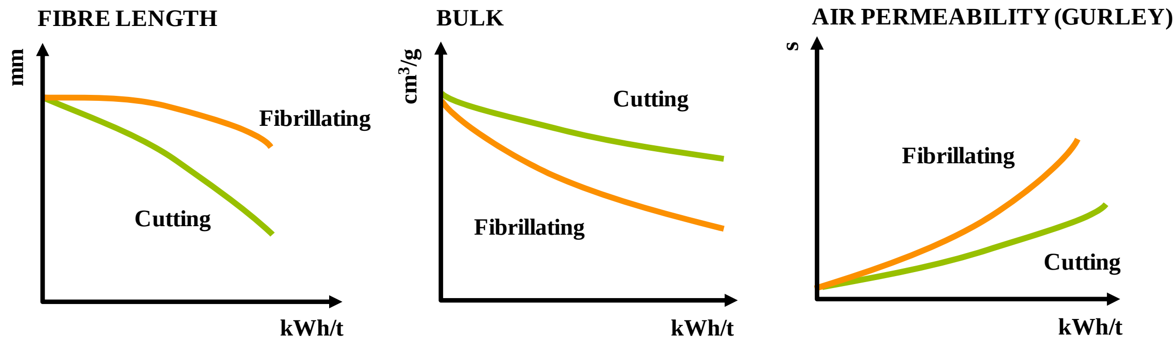


Figure 4 The effect of refining on fibre length, bulk and air permeability of paper (based on the material of Metso 2008a)

Refining decreases the spaces between the fibres and the pore volume of paper. This gives an explanation for the reduced air permeability[8] (stronger with fibrillating)(Figure 4) and the improved formation of paper (stronger with cutting). (VTT Industrial systems 2009) However, fibre shortening is not so desirable an effect in most cases, especially, when reinforcement pulp is being refined. (Koskenhely 2007, 99)

2.3.2 Strength properties

The fibre bonding area increases when the fibre structures open. Flexible and fibrillated fibre reaches many points of attachment with other fibres and the paper tensile and the bursting strength will grow. On the other hand the amount of fines increases and fibres swell which is observed as a rise in the SR number[9]. At the beginning of softwood pulp refining the tear strength will grow because fibre bonding is improved. When refining is proceeded the tear strength collapses and this is perceived due to weakened fibres. In that case, fibres have broken and less tear energy is needed. When fibres are withdrawn unbroken the energy is higher. (Figure 5)(VTT Industrial systems 2009)

[8] Gurley method measures air flow through paper and reports the result in sec/100 ml
[9] The Schopper-Riegler value (°SR) measures drainability of pulp (10 ml water is 1 °SR)

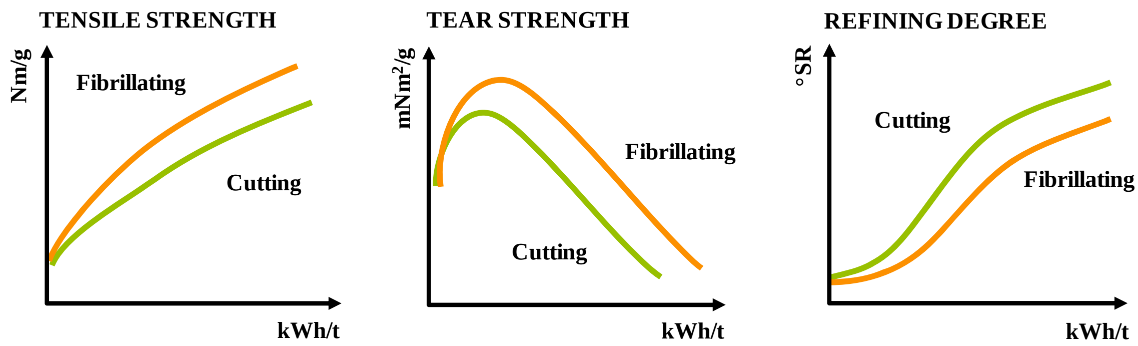


Figure 5 The effect of refining on tensile strength, tear strength and drainability (based on the material of Metso 2008a)

Tensile strength development as a function of the SR number depends on the Specific Surface Load (*SSL*). Figure 6 illustrates that the lowest *SSL* achieve the best tensile index when the Specific Edge Load (*SEL*) is equal. If fibrillating refining is desired the *SSL* must be low and if cutting refining is desired the *SSL* must be high with the same *SEL*. (Metso 2008a)

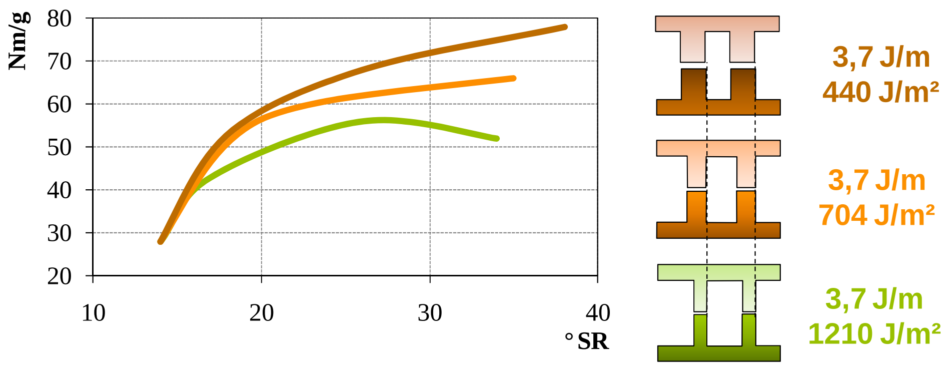


Figure 6 Intensity of refining when bleached pine sulphate pulp is refined (based on the material of Metso 2008a)

2.3.3 Optical and surface properties

Optical paper properties such as opacity, light scattering coefficient and brightness are reduced by refining. When the arriving light hits the barrier layer of the paper, which is optically looser and denser material, part of the light will: diffuse reflected, bounce directly, permeate through the paper and be absorbed (Figure 7). The proportions of these phenomena depend on the size of the fibre-air barrier layers and the amount of diffusing particles. (VTT Industrial systems 2009)

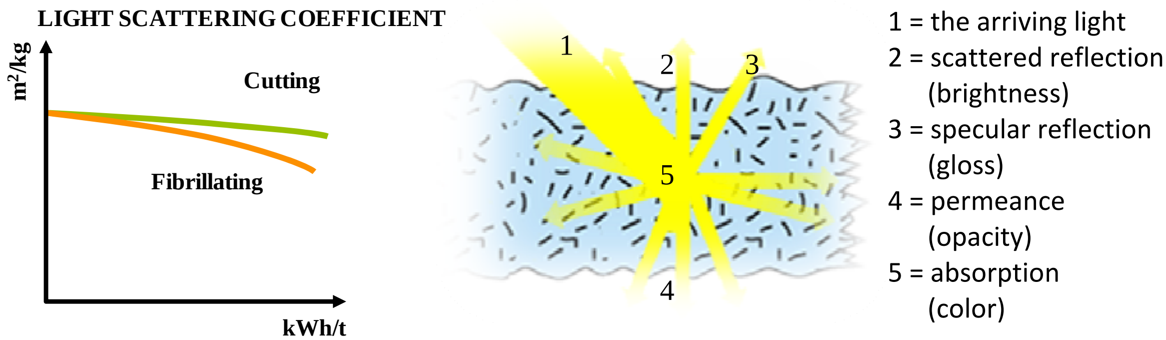


Figure 7 The effect of refining on the light scattering coefficient and contact of light and paper (based on the materials of Metso 2008a and VTT Industrial systems 2009)

Refining widens the outer surface of fibres and the light scattering coefficient grows. However, when fibres and fibre fines form hydrogen bonds they approach so close to each other that they are in so called optical contact (spacing < 0.05 µm). In that case, the fibre-air barrier layers have disappeared in optical meaning and optical properties have deteriorated. There is often noticed an interdependence between density of paper, the tensile strength and the light scattering coefficient. Typically, while the density of the sheet grows alike the tensile strength increases (more bonds) so the light scattering coefficient is reduced. (VTT Industrial systems 2009)

The paper surface properties change in refining, due to formed flexible fibres which shapes the surface of paper and smoothness is improved (Figure 8). (VTT Industrial systems 2009)

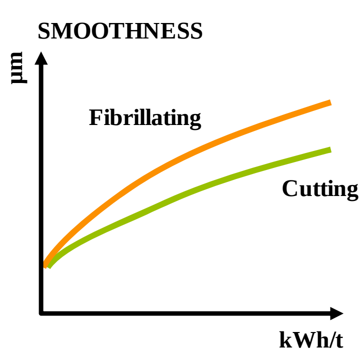


Figure 8 Smoothness (PPS) development as a fuction of the *SRE* (based on the material of Metso 2008a)

2.4 Factors affecting the axial force in low-consistency refining

The refining process is controlled to attain desired properties for paper or board. The refining line starts from the refiner feed chest where pulp is pumped in controlled consistency to the first refiner. Pulp is pumped from the first refiner to another and eventually refined pulp flows to the blending chest. Number of refiners depends on targets of fibres modification. However, single refiner can be controlled by the following figure. (Figure 9) (VTT Industrial systems)

Quality control	• Drainage control • Quality optimization
Refining control	• SRE control • Power distribution
Refiner controls	• Motor power control • Gap clearance control

Figure 9 Refining control with Kajaani method (VTT industrial systems 2009)

The gap clearance is controlled with the loading device which moves the shaft unit and the rotor in axial direction. When the rotor is moved towards the stator, the gap clearance becomes smaller. The flowing fibre suspension produces forces in axial direction and intensity of this force depends on geometry of the fillings and the rotor motion. (Figure 10)

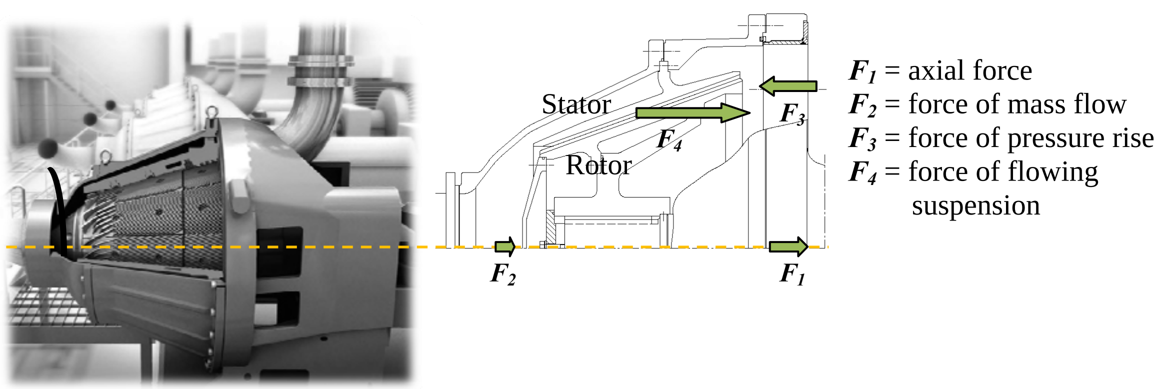


Figure 10 Axial forces on rotor in the conical refiner (original picture: Metso 2010)

This part analyses factors affecting the axial force in three parts. First, the flowing fluid effect is examined. Then, the rotor motion is considered and this way the geometry of fillings was figured out.

2.4.1 The fibre suspension

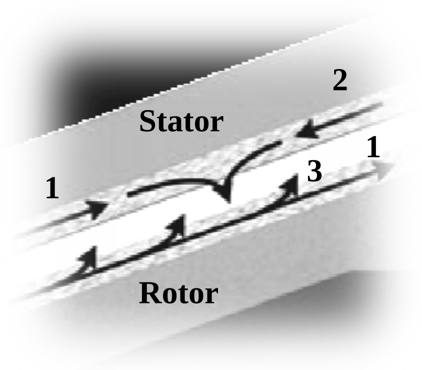
Pulp which is fed to refiner is suspension of water, chemicals and wood fibres. These fibres form flocs already in low consistency (2 – 6 %). Existing shear forces of refining breaks up and form flocs continuously. (Lumiainen 2000, 97) In addition, fibre flocculation influences morphology of fibre and the liquid viscosity. Longer fibres create larger flocs whereas increasing liquid viscosity reduces the floc size. (Lundin 2008, 63; Paul, Duffy & Chen 2001)

Water temperature, pressure and pH have an effect on fibres. Hot water dissolves hemicelluloses which are seen as deterioration of the paper strength properties. Water penetrates to the fibres easier in high pressure and often this pressure is given by the process. Water penetration makes fibres more flexible and it is ensured with sufficient retention time (min. 1 hour) in the refiner feed chest. Acidity of suspension affects water penetration too. When pH is below 5 water penetration decreases, and if pH is over 10 fibres becomes slippery. So, suspension should be close to neutral (pH 7). (Metso 2008a)

The flocculation of fibre suspension is estimated to raise the axial force. An aggregation of fibres in fibre suspension presupposed to hold out as long as possible. Large and stable flocs probably produce larger axial force.

2.4.2 Rotor motion

When the fibre suspension flows to the refiner, the rotating motion of the rotor creates hydrodynamic forces in the refining zone. These forces are depending on rotational speed and radius of rotor. When suspension flow is examined it is noticed that there are three main flows: stock flow, vortex flow and back flow (Figure 11). (Lundin 2008, 65; Metso 2008b)



1 = stock flow

2 = back flow

3 = vortex flow

Figure 11 Flow pattern between the rotor and the stator fillings (Metso 2008b)

The refining system is designed so that a low-consistency refiner generates small positive pressure over the refiner. Hydraulic capacity of the refiner depends on consistency of pulp, size of refiner, rotation speed, openness of fillings and rotation direction (Figure 12). (Metso 2008b)

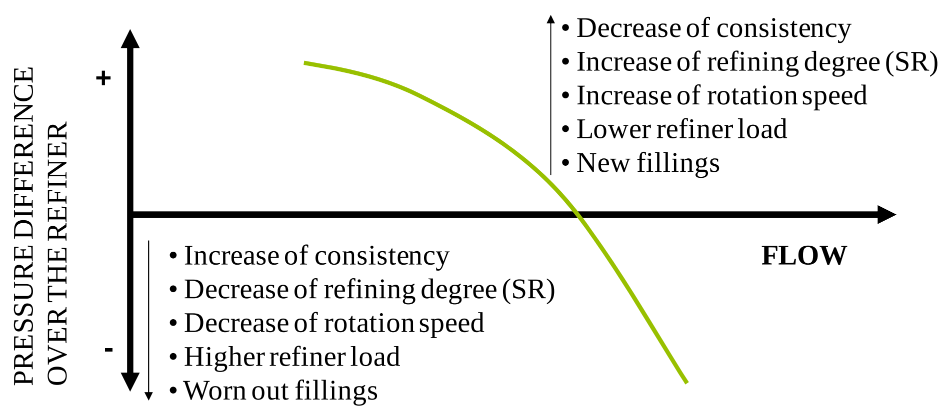


Figure 12 Hydraulic capacity of refiner (Metso 2008b)

Higher pressure difference over the refiner strengthens the back flow. Pressure and flow of the suspension produce forces that affect the axial force. Inflow of suspension grows axial force and pressure after the fillings generates antagonistic force. Liquid and solids of suspension generate normal force on the surface of rotor which is also active in axial direction. In addition, the flowing suspension has a friction force which affects the axial force. (Ala-Hongisto, Koskenhely & Nuutinen 2006)

The following equation is formed by using the balance of force in axial direction of the rotor. Measured axial force F_{ax} (N) with constant speed in conical refiner is

$$F_{ax} = (F_{in} - F_{out}) + \left(F_{P,l} + F_{P,s}\right) \sin\alpha + F_{visc} \cos\alpha \qquad (10)$$

where F_{in} and F_{out} (N) are forces of inflow and outflow of suspension in axial direction that are produced by pressure and flow of the suspension. $F_{P,l}$ and $F_{P,s}$ (N) are liquid and solids of the suspension generated normal forces on the surface of rotor and F_{visc} (N) is a friction force of flowing suspension that has a component in axial direction. (Ala-Hongisto et al 2006)

Axial loading force of rotor produces loading force between the bars. Distance between the bars is called gap clearance which depends on axial movement of the rotor. The loading force F_{load} (N) and the gap clearance change $\Delta\ GC$ (mm) are calculated for conical refiner as

$$F_{load} = \frac{F_{axial\ load}}{\sin\alpha} \qquad (11)$$

$$\Delta\ GC = \sin\alpha \cdot s_{alm} \qquad (12)$$

where $F_{axial\ load}$ (N) is axial loading force of rotor and α is angle between shaft and the surface of rotor. Axial loading movement is s_{alm} (mm). According to equation (12) if rotor moves 1 mm and flank angle α is 20° so gap clearance changes 0.3 mm. But then, when axial loading force $F_{axial\ load}$ is changed with same flank angle, the loading force F_{load} change is three times larger. (Figure 13) (Metso 2008a, Partanen 2010)

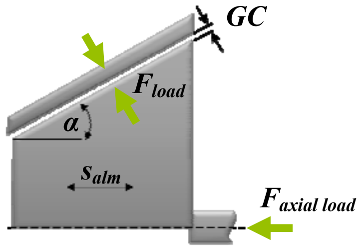


Figure 13 Loading force and the gap clearance in the conical refiner (original figure: Metso 2008a)

2.4.3 Geometry of fillings

Conclusion from previously parts is that refiner fillings are the governing components when paper quality and process is concerned. Designing of the fillings begins by evaluating the raw material furnish and desired pulp and paper quality (VTT Industrial systems 2009). Bar geometry affect the refining result and the axial force.

The rotor and the stator could be made from one solid piece (Figure 1 and 2) or from several segments (Figure 10). These refiner fillings are typically manufactured from martensitic stainless steel by casting. Other materials like high chrome iron, NiHard and ceramic materials are also used. Filling castings surface is machined and the rotor is balanced. Filling casting could be treated with heat, when the final characteristics of fillings are adjusted. (Lumiainen 2000, 115 – 116; Partanen 2010)

Dimensions of bars and grooves and angle of bars form bar pattern of refiner fillings. In addition, dams between bars are sometimes used especially when reject pulp is refined. (Lumiainen 2000, 115) However, using of dams has been reduced because dams produce more of short fibres and cause uneven wear of bar surfaces. (Koskenhely 2007, 117) When bars cross each other they form angle which is called intersecting angle. This angle varies from 10° to 40°. (VTT Industrial systems 2009) Typical dimensions of bar pattern are given in figure 14.

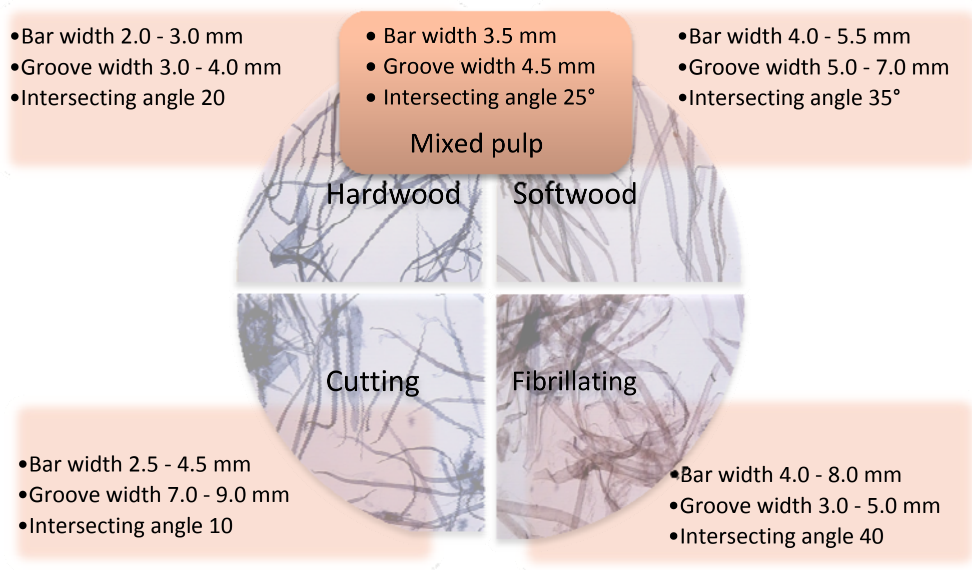


Figure 14 Typical bar pattern for different applications (pictures from VTT Industrial systems 2009)

Material of fillings should have good dimension stability so the refining conditions stay stable. Corrosion and wear of the fillings depend on material as well as on the used process conditions. (Lumiainen 2000, 116) If refiner fillings are loaded too much or the material of refiner fillings is too soft, the edges of bars begin to round. Then the refiner load grows alike the axial force. (Metso 2008a) On the other hand, wear of bar edge radius depends on metal composition[10]. Bar could wear from the edge or in horizontal direction. Horizontal wear forms sharper edges when better energy efficiency is achieved. (Koskenhely 2007, 128)[10,11]

2.4.4 Summary

The following table is pulling together the data of factors affecting the axial force (Table 1). Axial force is estimated to grow when the following factors appears in low-consistency refining. Theoretical consideration is based on fibre flocculation, fibre suspension flow,

[10] Original source: Baker, C.F. 2003. Refining and improved paper machine runnability. In: proceedings of 7th PIRA international refining conference & exhibition
[11] Original source: Siewert, H. & Selder H. 1976. Energiewirtschaftliche Aspekte der Ganzstoffmahlung.

amount and nature of refining. The retention time of fibre flocs in the refining zone is thought to be an effective factor, as well as flow pattern on and after the refining zone.

Table 1 Estimation of factors that increase the axial force

Fibre suspension	Rotor motion	Geometry of fillings
•long fibres	•low rotation speed	•worn out fillings
•coarse fibres	•high refiner power	•fine fillings
•stiff fibres	•small gap clearance	•high flank angle
•low liquid viscosity	•high production level	•high radius of fillings
•high inflow pressure		•too big or small intersecting angle
•high pressure difference		•dams
•high consistency		•wide bar
•low refining degree (high CSF, low SR)		•many bars
•dried fibres		•more bars in stator
•short wetting time		•small groove
•pH over 10 or below 5		•tilted bars
•high temperature of pulp		

The effect of fibre flocs on axial force was assumed to be the strongest. Especially, the behaviour of these flocs between the refiner bars. The stage of flocculation is depending on fibre suspension and the flow behaviour from fillings.

Time of flow could be decreased with flow channels between the bars, when objective is to reduce the axial force. Risk of minor refining effect on flocs, and hence undesired paper properties could be the result.

3 Experimental

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4 Conclusion

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Appendices

Appendix 1: Refiner trial plan

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Appendix 2: Measured process values

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Appendix 3: Measured hand sheet values

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Appendix 4: Length weighted fractions

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