MASTER´S THESIS

SIMO MERTANEN 2016

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Master's thesis

Brown stock washing upper level control utilization at hardwood fiberline

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TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Hakusanat: Ruskean massan pesu, ylemmän tason säätö, pesuhäviö

Ruskean massan pesu suoritetaan keittokemikaalien ja orgaanisen aineksen talteenottamiseksi sekä ylimääräisten epäpuhtauksien kuten metalli-ionien ja uuteaineiden poistamiseksi. Ylimääräinen liuennut orgaaninen aines kuluttaa valkaisukemikaaleja ja talteen otettuna se voidaan muuttaa polttamalla energiaksi.

Ruskean massan pesuvaiheen tehokkuutta voidaan seurata laimennuskertoimen ja pesuhäviön avulla. Laimennuskerroin määrittää sellutonnia kohden käytetyn pesuvesimäärän ja pesuhäviö pesemöltä poistuvassa massasuspensiossa olevan liuenneen aineksen määrän, jota ei saatu pestyä pois.

Tämä diplomityö keskittyy ruskean massan pesemön ylemmän tason säädön käyttöönottoon ja optimointiin. Säätö perustuu reaaliaikaisiin massasuspensioiden ja suodosten kuiva-ainemittauksiin ruskean massan käsittelyn eri prosessivaiheissa. Online-mittausten avulla määritettiin prosessin kemiallista tilaa ja säädettiin koko pesemön kattavaa laimennuskerrointa sen mukaisesti.

Koeajoja, joihin kuului syöttösakeus, pesurien momentti, pesuveden lämpötila ja laimennuskerroin suoritettiin eri muuttujien vaikutuksia pesuhäviöön tutkittaessa. Ylemmän tason säädön vaikutusta klooridioksidin kulutukseen tutkittiin pidemmän aikavälin koeajolla. Tulosten perusteella pesemön ylemmän tason toimintaa kehitettiin käytettävyyden, toimintavarmuuden ja pesutehokkuuden parantamiseksi.

Ylemmän tason säädön käyttöönotto onnistui ja siitä tuli ensisijainen pesemön ajotapa. Säädön todettiin optimoivan pesuveden käyttöä, tasoittavan prosessin heilahteluja ja siten vähentävän pesuhäviötä ja klooridioksidin kulutusta merkittävästi. Määrittelemällä laimennuskerroin tarkasti voidaan vähentää haihduttamon kuormaa ja saada tasaisen hyvä pesutulos.

ABSTRACT

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Brown stock washing upper level control utilization at hardwood fiberline

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Instructor: Kirsi Riekkinen DI
Examiners: Professor Eva Jernström

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Washing of brown stock pulp is done to recover cooking chemicals, remove impurities such as metal ions and bleaching chemical consumptive ingredients from the pulp suspension and to salvage organic matter that can be turned into energy by burning. Washing stage performance can be evaluated by the dilution factor, which determines the water amount used for pulp ton, and washing loss, which determines the amount of washable components in pulp discharged with pulp to bleaching that could not be washed away.

This study focused on utilization of brown stock washing stage upper level control, which was based on the real time online measurement of total dry solids of the pulp suspension and washer filtrates in several points of the process. Online measurements were used to determine the chemical state of the process and adjustments to dilution factor made accordingly.

Trial runs including feed consistency, washer drum torque, washing water temperature and dilution factor were made to examine the effect of different variables to washing result. A longer test period was also made to determine the upper level effect on the chlorine dioxide consumption. According to results, improvements to upper level control were made to enhance the functionality and efficiency of the washing stage.

Utilization of the upper level control was successful as it became the primary way of operating the washing stage. Upper level control was found to optimize wash water usage, level out process fluctuations and thereby decrease the washing loss and chlorine dioxide consumption significantly. Possibility to define precise dilution factor for the whole washing stage decreases evaporation plant load and enables more stable washing result.

PREFACE

This master's thesis was done at UPM Kaukas mills at Lappeenranta during the period May 1. – October 31. 2015. The thesis was supervised by Kirsi Riekkinen and Eeva Jernström.

At the beginning I would like to thank UPM for offering me this excellent opportunity to deepen my knowledge and solve the mysteries of brown stock washing. I wish to thank all the operators and other personnel at fiberlines, who assisted and offered their knowledge to help me during this work. I also owe special gratitude to the excellent women at pulp mill laboratory for patiently analyzing the samples from the trial runs, I could not have done this without you. I also would like to show appreciation to Kirsi and Eeva for supervising this project, Matti Siitonen and Tomi Juuti for assisting me with technical details.

Last I would like to express profound gratitude to my loving girlfriend Mari, who has given her best to support me with this battle. The journey has been long, but even the slowest train reaches its destination finally.

Lappeenranta 2015

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ABBREVIATIONS AND SYMBOLS

ADt	Air dry metric ton
AOX	Adsorbable organic halogens
E_{APE}	Actual Process E-value
COD	Chemical oxygen demand
CCD	Charge coupled device
C_0	Pulp feed consistency
C_1	Discharge consistency
DF	Dilution factor
DR	Displacement ratio
D_0	First chlorine dioxide bleaching stage
TDS	Total dissolved solids
E	Efficiency value
Evap	Evaporation
HeXA	Hexenuronic acid
L_0	Liquor amount in pulp feed
L_1	Liquor amount in discharged pulp
MC	Middle consistency
$NaSO_4$	Sodium sulfate
nD	Refractive index
NEF	Norden efficiency factor
S	Shower flow
V_1	Washer filtrate flow
V_2	Washer wash liquor flow
X_0	Concentration in pulp feed
X_1	Concentration in discharged pulp
Y	Wash yield
Y_1	Concentration in washer filtrate
Y_2	Concentration of wash liquor
ϕ	Consistency of pulp
ΔC	Concentration gradient

INTRODUCTION

Modern pulp mills are more productive, cost efficient, and environmentally friendly than before. Usage of valuable resources, such as water and chemicals are being minimized as water circulations are slowly being closed and chemical feeds optimized. At the same time tightening regulations for mill effluents promote the research and development for more controlled and stable processes with fewer process disturbances.

Brown stock washing can be considered one of the key elements when considering pulp mill efficiency and cost effectiveness as ashing stage performance has huge impact to the rest of the mill. Optimal usage of washing water minimizes the load of evaporation plant and at the same time lowers the need of bleaching chemicals and effluents to environment. As a result pulp quality can be kept stable and unit costs low. Precise operation of the washing stage requires precise functionality from process equipment and measurements, as well as well executed controlling of key parameters from both software and operators.

This master's thesis consists of three parts. Literature review explains the phenomena's and objectives behind brown stock washing, illustrates the principle and devices of dry solids measurement and ways to evaluate brown stock washing effectiveness and influences to costs.

In the experimental part the effect of upper level control is evaluated by measuring the wash water usage and washing loss from washing stage to bleaching. Several trial runs, including feed consistency, drum torque, dilution factor and wash water temperature were also made to obtain knowledge of the effect of certain key parameters influence to washing loss. Then results are presented and discussed.

At the final part, conclusion and suggestions to the future are made.

1 BROWN STOCK WASHING

After cooking pulp fibers are suspended in cooking liquor, which contains cooking chemicals and other dissolved organic and inorganic matter. The pulp suspension consists of free liquor phase and fiber phase which also includes the entrained liquor inside the fibers. Free liquor is quite easy to separate from the fiber phase during washing, but entrained liquor can be removed only by capillary forces and diffusion. Diffusion occurs by concentration differences and requires sufficient time to happen. (Sillanpää 2005)

Pulp washing influences mill processes in various ways. Properly done washing of pulp minimizes the cooking chemical loss and lowers the need of make-up chemicals, limits the carryover between process stages, maximizes the collection of burnable organic substance, such as lignin and minimizes the usage of bleaching chemicals. In addition, as a result of all the preceding, clean pulp with good mechanical properties can be produced. (Sixta 2006)

One of the biggest factors in mill-scale optimization and increasing the washing performance is minimizing the process fluctuation and oscillation. Stable tank levels, pulp properties and consistency, wash water usage and other variables are crucial to optimal washing result. Pulp should be fed to the washer with minimum amount of dirty liquor to minimize the energy and washing liquor consumption. In countercurrent washing line all excess water added to last washing step increases the load in evaporation plant and the need of electricity for pumping. (Richardson 2005)

Pulp should be washed with minimum amount of fresh water, in order to limit the load to other departments in the mill, but with enough water to remove all the unwanted substances from the pulp. In general, washing is always balancing between evaporation costs and bleaching costs.

Before bleaching, cooking liquor has to be separated from fibers by washing. Main reason for this is the recovery of the valuable cooking chemicals, which would otherwise have to be replaced with expensive make-up chemicals. Not only are they a valuable resource for the mill, recovery also reduces water pollution rates significantly. (Santos & Hart 2014)

Second reason is the recovery of organic compounds. Organic compounds can be converted into process steam and electricity by burning them in recovery boiler. Pulp mills can be considered energy independent as all energy and electricity used in pulp manufacturing comes directly from wood based materials. Forest industry can be considered as a pioneer and a leader in renewable energy as pulp mills produced 80 % of all renewable energy in Finland in 2013. (Metsäteollisuus 2013)

Third reason is the removal of unwanted components, such as metals, pitch and extractives. Metal ions, such as manganese cause problems as they react with peroxide and cause its deterioration into harmful radicals and pitch with other extractives are problematic as they cause quality problems and accumulate to process equipment. (Santos & Hart 2014; Sun *et al.* 1999; Kopra 2015)

1.1 Washing principles and phenomena

As said before, cooking liquor contains a lot of component that have to be removed from the pulp suspension. On each section of displacement washing, cleaner wash water is added on top of the pulp mat to displace the dirtier water with the help of pressure difference. Optimum result is achieved when all the dirty water is uniformly replaced with clean shower water without any mixing happening (figure 1). (Santos & Hart 2014; Sixta 2006)

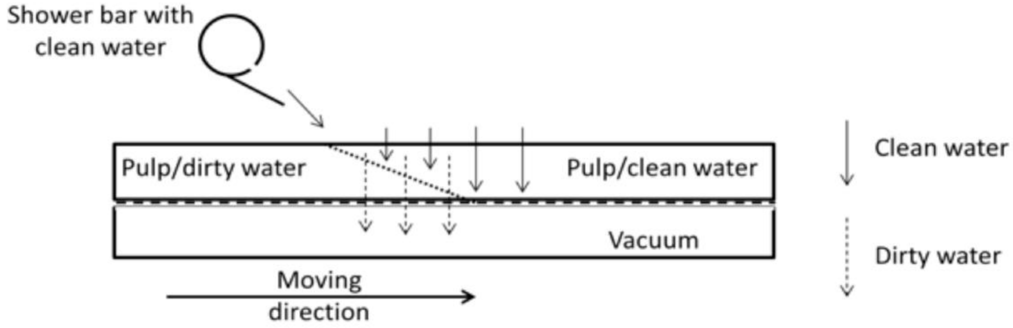


Figure 1 Mechanism of displacement washing. (Santos & Hart 2014)

Displacement velocity, pulp pad thickness, pulp consistency and operating temperature are considered to be the most important variables in displacement washing. Also pH affects the drainage rate, and is known to be best around 9,5. These factors have been studied mainly in brown stock washing as it is the most important washing step and defines efficiency of other subsequent stages performance. (Sillanpää 2005; Sixta 2006)

1.1.1 Fractional washing

Controlling carry-over between washing stages requires efficient washing. Fractional washing offers a way to utilize different chemical composition washing liquors in washing, originating from the same source. This is done by dividing the filtrate into several different fractions and using them in different parts of the washer. Quick leaching components in the pulp suspension, such as metal ions and cooking chemical removal can be enhanced with fractional washing. The principle is presented in figure 2. (Joronen *et al*. 1998)

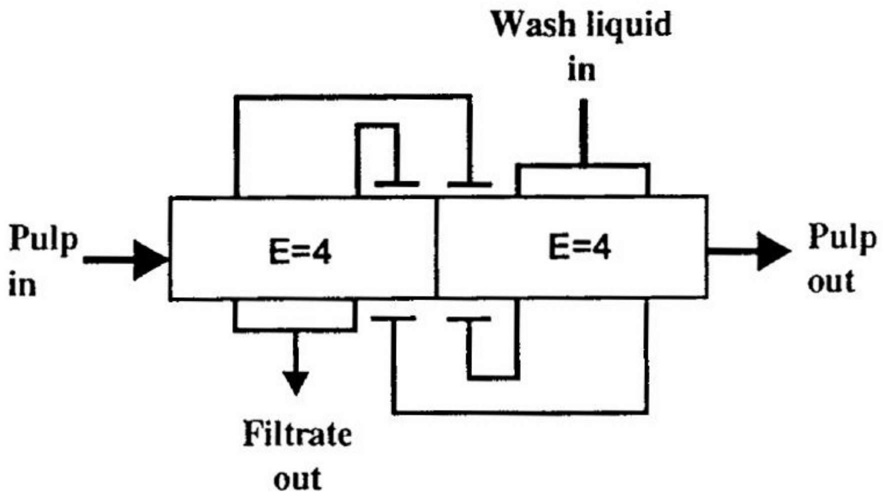


Figure 2 Principle of fractional washing with Norden efficiency factor of 4. (Joronen *et al.* 1998)

1.1.2 Displacement velocity

Flow of washing liquor through the pulp mat follows Darcy’s law, which determines laminar flow rate through porous media. Affecting factors of the phenomena are pressure difference, which increases the drainage velocity and secondly the permeability of the pulp mat. Hardwood fiber based pulp mat has greater drainage resistance value compared to softwood and it increases rapidly when fiber concentration is increased, resulting the washing liquor to flow through the mat at considerably lower rate. (Sixta 2006)

Drainage, or displacement velocity and thereby the minimum time for the dirty liquor to be displaced with cleaner one is also affected by the viscosity and the temperature of the liquor. Higher solids content increases the viscosity, slowing down the liquor flow, but on the other hand higher temperature lowers the viscosity. (Sixta 2006)

As long as the voids in fiber suspension are filled with liquor and not air, the displacement can be thought to happen as described above. When pulp flow contains considerable amount of air trapped within the fiber suspension, the air bubbles block the liquor flow routes inside the mat causing the drainage time to increase and washing result to deteriorate substantially. (Sixta 2006)

In real process situations best washing result is achieved by implementing high pressure difference, optimal mat thickness and using high temperature to ensure good flow properties due to low viscosity of the liquor. Improving drainage rate means higher outlet consistency and therefore better washing result. It is nevertheless important to notice that some mixing of dirty liquor and the wash liquid always happens and displacement is not uniform due to turbulence and small scale channeling. (Santos & Hart 2014; Sixta 2006)

Also cake thickness and particle geometry affect the interstitial velocity and therefore washing efficiency. As the geometry of the particles remain relatively the same, cake thickness and porosity are mostly affecting the displacement ratio. The higher the thickness and porosity, the better diffusion and thereby better washing result. This is true up to a certain cake thickness. After the cake becomes thick enough, the pressure drop across the cake decreases too much and washing result deteriorates. (Kurkreja & Kray 2009; Kurkreja & Kumar 2012)

1.1.3 Diffusion

Diffusion controls the substance exchange between the free liquor and entrapped liquor within the fibers. It can be described as the thermal motion of the molecules trying to level concentration differences. (Sixta 2006)

There are several factors that are influencing the rate diffusion happens. Concentration gradient ΔC determines the speed of particle movement from higher concentration to lower. The rate of diffusion is directly proportional to concentration gradient. Dilution decreases the concentration within the system, and therefore increases the rate of diffusion. The higher the concentration difference, the faster the diffusion. (Santos & Hart 2014)

Diffusion is also a rate of distance and temperature. Diffusion is fast over short distances, but decreases rapidly with growing distance. Motion of atoms increases with growing temperature and therefore speeds up diffusion. Motion of atoms is also related to atom size and pressure. Smaller atoms, such as sodium diffuse faster and increased pressure increases the rate of diffusion. In addition diffusion time is critical especially with high concentration washing operations after the digester. As the washer drum rotates too fast, diffusion time for decomposition products of lignin, carbohydrates and extractives can decrease to insufficient level. (Sixta 2006; Kopra 2015)

1.1.4 Temperature

Temperature of the washing liquid can affect washing result dramatically. Solubility of excess organic and inorganic matter in pulp mat is temperature dependent and the higher the washing liquid temperature, the lower the viscosity and therefore increased filtration capacity of the pulp mat. Increase in shower water temperature lowers liquor viscosity and allows greater diffusion to fibers. Only limitation to temperature is the possibility of flashing in washers drop leg. Normal operation temperature varies between 80 - 90 °C. (Richardson 2005)

1.2 Equipment

Unbleached pulp is typically washed with drum displacement washers, also known as DD-washers (picture 1). It is common that the first two washers are installed parallel and after oxygen stage there is only one washer. DD-washer consists of a large cylinder with several axial compartments. The bottom of each compartment has a perforated plate for dirty liquid to be displaced with cleaner liquid sprayed over the pulp suspension at each washing step. (Sixta 2006; Pikka *et al*. 2003)

Picture 1 Brown stock washers at hardwood fiberline.

Figure 3 illustrates the main components of typical DD-washer. Pulp is fed through an inlet (1) to a compartment where pulp suspension faces the perforated plate and forms a cake (2). Rotating cylinder then moves the cake through different washing sections (3,4,5) which are separated from each other by seal bars. After the washing section pulp cake enters the vacuum section (6), where most of the free liquor is sucked out of the pulp mat and then the cake is discharged with compressed air (7). Washing liquor circulation is to the opposite direction of the pulp. Cleanest wash water is fed to last washing section (10) and the dirtiest wash liquor leaves the washer from the first washing stage of pulp (8). Free liquid from vacuum section is circulated to washing liquor feed (9). (Pikka *et al.* 2003)

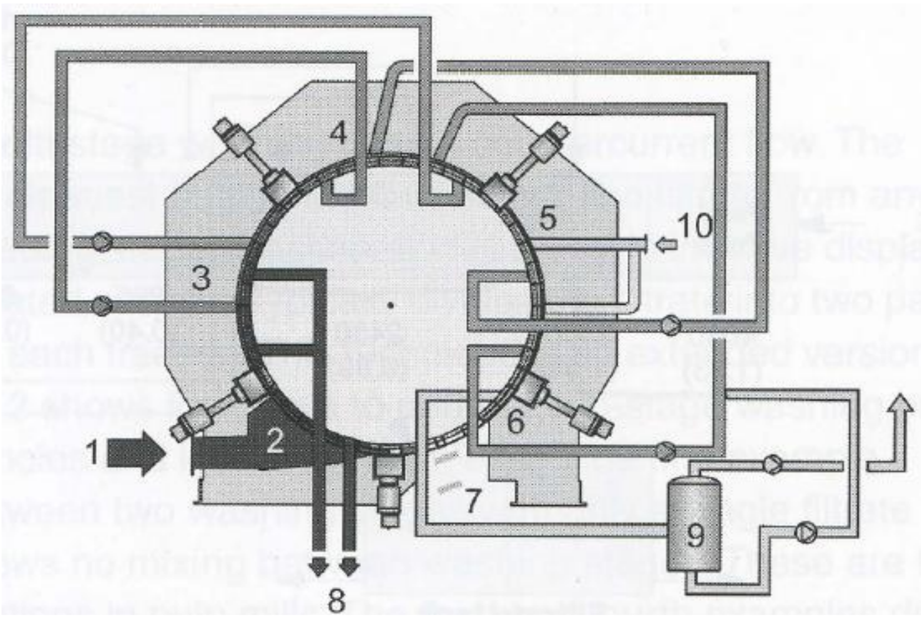


Figure 3 Typical DD-washer main components and operating principle. (Pikka *et al*. 2003)

DD-washer operates with 6 most important input variables (Figure 4). These are production speed, drum torque, feed pressure, pulp consistency, dilution factor and wash water temperature. The output variables where the performance of the washer can be evaluated are the discharge consistency and washing loss, which can be divided into organic and inorganic portion. Wash loss on the picture represents the total amount of dissolved solid, including both organic and inorganic substances. Chemical oxygen demand (COD) is important as excess COD load causes bleaching chemical consumption and Adsorbable organic halogens (AOX) effluents. (Sixta 2006)

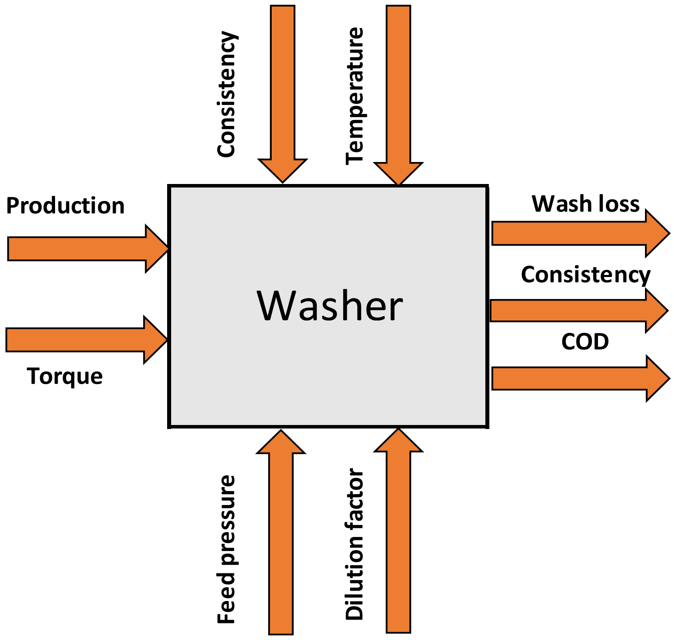


Figure 4 Factors affecting brown stock washing and variables that are followed to determine the performance of the washer. (Sixta 2006)

Pulp suspension with dissolved organic and inorganic compounds Enter the washer feed through an inlet vat, where pulp is spread from the incoming pipe to the width of the washer. Pulp is fed to the washer at the pressure of 20 - 40 kPa. For optimal washing result, the thickness of the pulp mat should be kept as uniform as possible. Drum torque determines the load of washer hydraulics, and can be seen as value of cake thickness on the drum. It is desirable to operate washer at higher torque as it results in slower rotation and better displacement. The best washing result is achieved when thickness is constant and feed pressure is set so, that the pulp mat has as uniform consistency in the z-direction. Using too high feed pressure causes the surface of the drum to close up deteriorating the liquor flow through the pulp cake and washing result. (Sixta 2006)

After the inlet pulp adheres to the surface of the washing cylinder through pressure difference and enters the wash zone as the washer rotates. Different washing compartments are sealed from each other with adjustable elements in order to get good washing liquid circulation throughout the washer. Poorly adjusted elements cause inadequate washing liquor circulation and bad washing result which causes problems later in the process. After washing sectors, pulp mat is discharged from the compartment with pressurized air. (Sixta 2006)

Typical DD-washer has 1 – 4 countercurrent washing stages, where the incoming, dirty pulp is washed with dirtiest liquid and the cleanest washing liquid interacts with the cleanest pulp. This basic idea (figure 5) is used to the whole washing line as well as for a single washer. A single brown stock washer can use up to 4 countercurrent washing stages. If the washing liquor circulation of a washer is interfered, consistency of the dirty liquor in the last washing stage increases and the washing result can decrease dramatically. This can be seen immediately from the conductivity measurement and later from the bleaching chemical consumption. (Sixta 2006; Gullichsen & Fogelholm 2003)

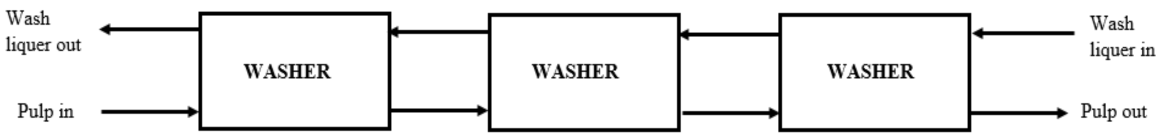


Figure 5 Principle of countercurrent washing. Cleanest wash liquor is introduced to cleanest pulp. (Sixta 2006)

Some pulp production operations are affected by foaming tendency of liquid. Brown stock washing is one of these. Foaming control in washing stage is crucial to process stability, pulp quality and also to chemical and energy costs. (Gullichsen & Fogelholm 2000) Silicone based antifoams are probably the most widely used to tackle problems with surface and entrapped air problems. Having very low viscosity, they spread rapidly on the surface of foam as tiny droplets. Effect of foam removal is based on the antifoam agent ability to spread air-liquid interface, causing the foam to collapse. (Bajpai 2015)

Washing stages can use many different types of process waters for brown stock washing. Many pulp mills use secondary condensate originating from the evaporation plant as it is reasonably clean, it is at rather high temperature and its amount is usually not limited. (Sankari *et al.* 2004a)

Secondary condensate is mostly water evaporated from the black liquor and should in optimal case contain only minimal fraction of other substances. Typically secondary condensate contains small amounts of methanol, organic acids, terpenes, phenols and dissolved gases. It can also in some situations contain black liquor and even fibers. (Blackwell *et al*. 1979; Serbas 1987) Most of the unwanted components of secondary that can cause COD can be removed by stripping. (Sankari *et al.* 2004a)

Some portion of unwanted contaminants is nevertheless always found in secondary condensate, so when trying to downsize brown stock washing COD, the cleanliness of the secondary condensate has to be taken into account. Conductivity and COD measurements are quite sufficient methods to analyze the chemical state of the condensate as lignin and methanol contribute COD and conductivity inorganics. (Sankari *et al.* 2004a)

1.3 Mathematical modeling of washing

Several models for evaluating washer performance have been created. Most commonly used models are the dilution factor, washing yield and Norden efficiency factor. A single washer or a washing system can be described as in figure 6 where C_0 represents the feed stock consistency, C_1 discharge stock consistency, L_0 and L_1 the amount of liquor with pulp in the inlet and outlet flows, V_1 and V_2 filtrate and wash liquor flows. These are represented as mass flow rate of liquid to mass flow of fiber. Variables X_0, X_1, Y_1 and Y_2 represent the solute weight fractions in L_0, L_1, V_1 and V_2. (Kopra 2015)

Figure 6 Determination of material flows in a separate washer or a washing system. (Kopra 2015)

Amount of wash water used is most commonly represented as dilution factor DF. Dilution factor defines the net amount of wash water added compared to that with the pulp. When DF is 0, black liquor in the pulp pad has been replaced by an equal amount of wash water. DF can be calculated from equation 1, where V_2 is the wash liquor amount and L_1 is the amount of liquid exiting the washer with pulp. (Sixta 2006)

$$DF = V_2 - L_1 \qquad (1)$$

Where	DF	Dilution Factor t/ADt
	V_2	Wash liquid amount
	L_1	Liquid exiting the washer within the pulp

Negative dilution factor tells us that the wash liquor amount has been smaller than the exiting liquor with the pulp and some of the dirty liquor has been left in the pulp suspension as carryover. Washers achieve better washing result operating at positive dilution factor, but the amount is limited by liquor penetration ability through the pulp mat. (Sixta 2006)

Operational limits in case of countercurrent washing are based on the fact, that dilution factor is determined by the last washer of the washing line. Using high dilution factor increases the washing result, but also seriously affects the evaporation plant and the waste water treatment capacity. (Sixta 2006)

Displacement ratio (DR) describes the actual washing process performance expressed in concentration. The result is expressed as a percentage of an ideal washing result and it is highly dependent on the washing liquor concentration. Therefore considerations concerning dilution factor should be made as it is valid only for one dilution factor, when concentrations are known. (Sixta 2006)

Displacement ratio can be calculated from equation 2 where X_0 is concentration of dissolved substance entering the washer with pulp and X_1 the concentration of exiting dissolved substance in pulp. Y_2 is the concentration of dissolved substances in the washing liquid. (Kovasin 2003)

$$DR = \frac{X_0 - X_1}{X_0 - Y_2} \qquad (2)$$

Where	DR	Displacement ratio
	X_0	Dissolved substances in pulp feed
	X_1	Dissolved substances in pulp discharge
	Y_2	Dissolved substances in wash liquor

Washing yield represents the washing efficiency of a substance, most commonly in COD. It is a simple ratio between dissolved solids washed from the pulp and dissolved solids entering the washer. When defining wash yield, it is supposed that the washing liquid is clean. In many cases this assumption is false and thereby washing yield leads to inaccurate results. Wash yield is defined as

$$Y = 1 - \frac{L_1 X_1}{L_0 X_0} = \frac{V_1 Y_1}{L_0 X_0} \qquad (3)$$

Where	Y	Washing yield
	X_0	Concentration of examined property in pulp to washer
	X_1	Concentration of examined property in exiting pulp
	L_0	Flow of unwashed pulp
	L_1	Flow of washed pulp
	V_1	Filtrate flow

There are many mathematical models created in order to construct reliable tools for brown stock wash controlling and washer performance monitoring. The preceding equations are of importance, but the most widely used and the most practical is the Norden Efficiency Factor (NEF), also known as the E-factor. (Sixta 2006)

NEF, or E-value is defined as the ideal number of countercurrent mixing stages, which are equalent to a washing system. E-value is valid for only one washer and cannot be used to compare different washers' performance. Nevertheless it can be used to determine a single washers performance in different process situations. (Sixta 2006)

A washing system can consist of one or many different washers. For several independent washing steps, a combined efficiency can be calculated as a sum of the independent E-values. (Sixta 2006)

E-value can be calculated from:

$$E = \frac{\ln \frac{L_0}{L_1}\left(\frac{X_0}{X_1} - \frac{Y_1}{Y_2}\right)}{\ln\left(\frac{V_2}{L_1}\right)} \qquad (4)$$

Where	E	Norden efficiency factor
	L_0	Liquor in with pulp (in tons)
	L_1	Liquor out with pulp (in tons)
	X_0	Liquor in concentration (COD)
	X_1	Liquor out concentration (COD)
	Y_1	Filtrate concentration (COD)
	Y_2	Washing liquor concentration (COD)
	V_2	Wash liquor flow rate (t/h)

Since inlet consistency is quite hard to evaluate reliably in real life process, a new equation discarding the inlet consistency has been created. The E_{APE} (equation 5) as Actual Process

E-value is far more suitable for mill operations. It is dependent on the outlet consistency, which has to be known to utilize E_{10}. (Kopra 2012)

$$E_{10} = \frac{\ln\left[1 + \frac{DF(y_1 - y_2)}{L_1(x_1 - y_2)}\right]}{\ln\left(1 + \frac{DF}{9}\right)} \qquad (5)$$

Where	E_{10}	Actual Process E-value at 10 % consistency
	DF	Dilution factor
	L_1	Washed pulp tons of liquor/BDt of washed pulp
	X_1	concentration of dissolved solids in washed pulp stream
	Y_1	concentration of dissolved solids in wash liquor stream
	Y_2	concentration of dissolved solids in outlet liquor stream

2 WASHING LOSS

"*Wash loss is the amount of residual washable compounds in the pulp suspension, which cause additional chemical consumption or a decrease in the process response in the subsequent bleaching stage*". (Sillanpää 2005)

Washing efficiency is determined by how much solute a washer can remove from the pulp stream and how much washing liquid is used to achieve this. Traditional ways of measuring washer efficiency and carry-over are conductivity and the amount of sodium in pulp after washing. Due to oxygen delignification stage after first brown stock washers, sodium loss measurement is more complicated than before. Sodium addition in the form of sodium hydroxide or oxidized white liquor makes the actual washing loss evaluation less accurate. (Kopra 2015)

2.1 Washing loss composition

Strict environmental regulations and focus on cost efficiency has led to taking a closer look to inorganic and organic components of brown stock, which affect the functionality of the whole fiber line after first stage of washing. Chemical oxygen demand (COD) and Total Dissolved Solids TDS have partly replaced previous indicators for washing loss at least when online-metering became available. Environmental aspects, along traditional economical, have become more and more important while considering washing efficiency (Sillanpää 2005; Sixta 206)

Delignified pulp contains soluble material, which has to be removed before pulp fibers are bleached. Any extra material besides pulp fibers causes dramatic growth in bleaching chemical usage and therefore bleaching costs. There are two main categories in black liquor entering brown stock washing stage along pulp fibers, organic and inorganic. Organic fraction consists mostly of lignin, extractives and hemicelluloses where the inorganic fraction consists mainly from cooking chemicals. In order to operate washers at low washing loss level, these all should be monitored and process fine tuned accordingly. (Saturnino 2012)

Oxygen delignification stage is affected by the amount of washing loss. This can be seen from reactor temperatures, amounts of chemical used and from kappa reduction. Controlling washing loss has been somewhat complicated due to process time delays and alternating process conditions and therefore the functionality of oxygen delignification stages have varied. (Kopra *et al.* 2012)

2.2 COD

Chemical oxygen demand (COD) is defined by the amount of oxygen that is required to chemically fully decompose organic material solubilized in water. Typically COD is measured with strong oxidizer in acidic solution assisted with heat. Organic matter is oxidized and COD is measured titrimetrically or photometrically by the amount of oxidant consumed. COD is usually presented as g/l. (Boyles 1997)

Organic liquor components should be removed from pulp suspension as they can convert into harmful halogenated organic compounds (AOX) in the first D-stage. AOX stands for Adsorbable organically bound halogens and it determines the amount of halogenated organic substances in water. (Swedish Environmental Protection Agency) Chlorinated aromatic derivatives are hazardous to nature so the amount should be kept as low as possible. Chlorination takes place at the first chlorine dioxide bleaching stage and is known to be dependent on the amount of lignin entering the dioxide stage and the chlorine load. Chlorinated organic compounds are formed when intermediately formed hypochlorous acid and chlorine, which formation is promoted by low pH, react with lignin and hexenuronic acids. The reaction is rapid and most of the AOX formation happens during the first minute. (Germgard & Larsson 1983; Santos & Hart 2014; Lehtimaa *et al.* 2010)

Different researches have also stated that 30 – 80 % of AOX formation could be based on hexenuronic acid (HeXA) chlorination, but in a study by Lehtimaa *et al.* in 2010 was found that the amount of AOX formation in the D_0-stage was not significantly affected by the hot acidic stage, which is known to remove HeXA from pulp. This implies that at least most of the AOX originates from lignin fractions. (Lehtimaa *et al.* 2010)

Not all COD causing fragments are harmful to process. It is important to recognize the ones that have real effect later in the process and question the true reliability of COD as a wash loss indicator. Sankari *et al.* stated that the most important COD causing compounds are lignin in its many fractions and certain inorganic sulphurs. (Sankari *et al.* 2004b)

Organic carryover influences to bleaching costs and fiber properties, such as viscosity are well known but monitoring of dissolved organics is rarely done in adequate level. Washing result and wash water usage are too often considered as good enough. (Richardson 2005)

2.3 Birch extractives

In case of hardwood, deresination of the pulp is essential. Wood extractives cause several problems later in the process and in the end product. Hardwood deresination is far more difficult than softwood as birch contains 2 – 2,5 % of resins, which are mainly composed of sterols, betulaprenols, triterpenyl alcohols and fatty acids, steryl esters and small amount of resin acids. (Bergelin & Holmbom 2003; Björklund Jansson 2005)

Björklund Jansson examined the amount of different extractive components in 3 different mills after cooking, after oxygen stage and from the bleached pulp (Figure 7). Extractive amount is at its highest immediately after cooking and decreases substantially during the oxygen stage. Bleached pulp still contains some portion of the original amount of extractives, but most of them are removed during washing and bleaching. (Björklund Jansson 2005)

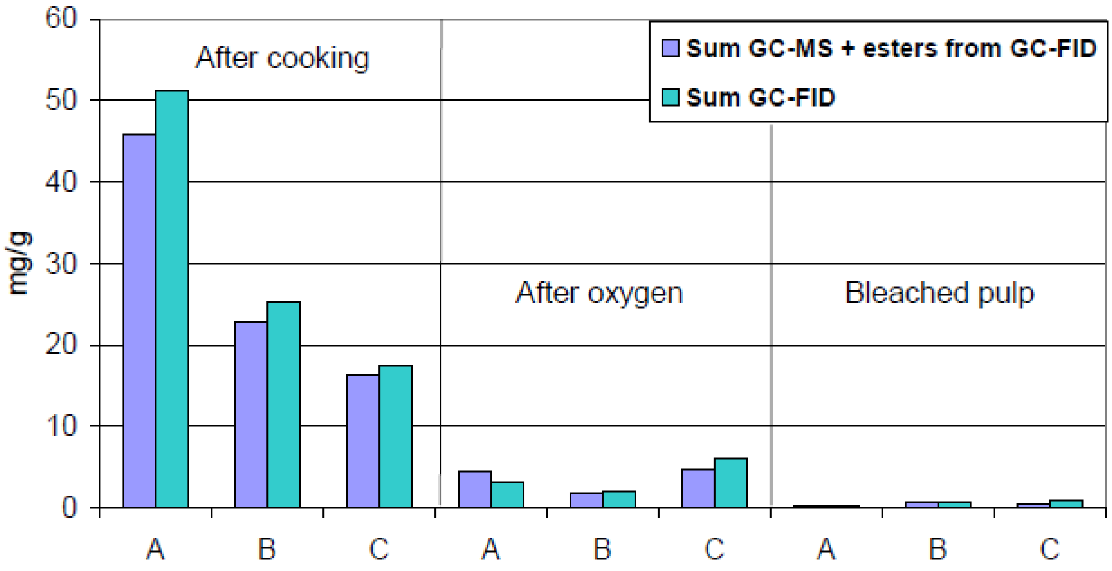


Figure 7 Birch extractive amount evaluated in 3 different mills. Determination was done after cooking, after oxygen stage and after bleaching. (Björklund Jansson 2005)

Birch extractives cause deposits in process equipment and dark spots in the end product that lower the quality. Deresination of the pulp is done by desorption of resin from pulp followed by washing and by oxidation of resin components to more hydrophilic form. Washing of resins that have more hydrophilic form is far more easier. Resin components are oxidized and converted to more water soluble form and can be thereby washed away more easily after oxidation stage. As seen on figure 8 saturated fatty acids are more difficult to oxidize as only slight change in fatty acid amounts happens during bleaching. Unsaturated fatty acids nevertheless are almost completely removed during bleaching. (Bergelin & Holmbom 2003)

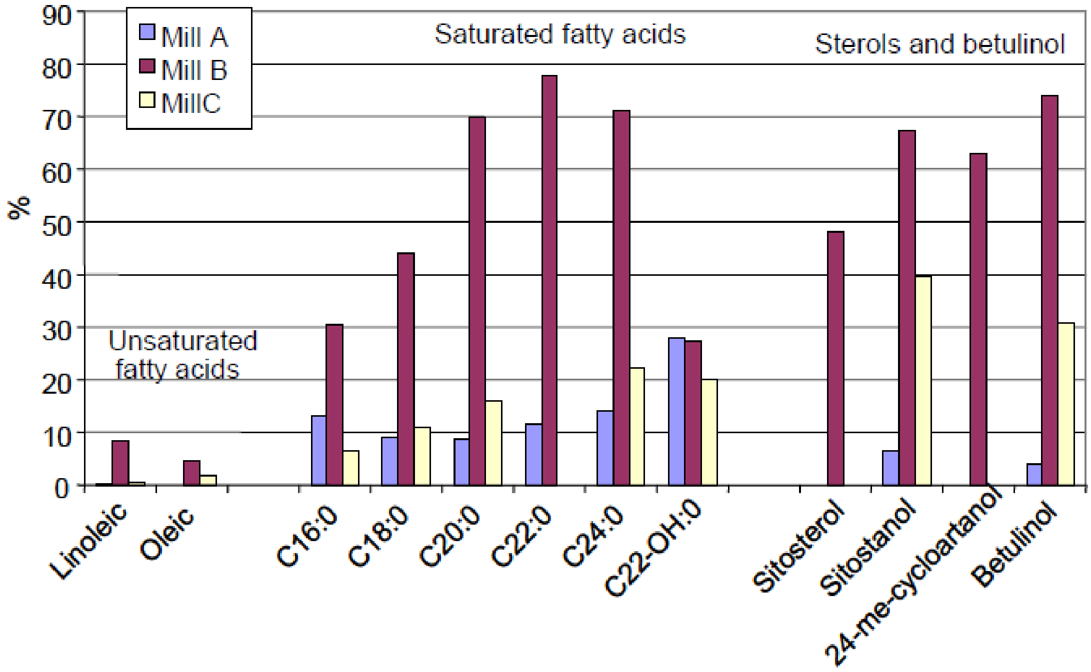


Figure 8 Remaining fractions in bleached pulp compared to pulp after oxygen stage. (Björklund Jansson 2005)

It has to be noted that attempts to close the water cycle at pulp mills due to environmental trends will increase the amount of birch extractives in the process water as there is clear relation between these two. (Bergelin & Holmbom 2003)

2.4 Measurements of washing loss

Until recent applications of refractometers, reliable and fast technique of monitoring carry-over at brown stock washing has not existed. Washing loss evaluations have been based on online conductivity measurements and slow laboratory measurements of NaSO4 and COD. Demanding process conditions and the need of very short response time has been a challenge in washing efficiency development. By using refractometers, it is possible to measure real time total dissolved solids TDS amount from a pulp suspension or from a liquid flow with a reasonable accuracy. (Kopra 2015)

Conductivity measures only the inorganic portion of the liquid while the dissolved organic proportion is left unmonitored. It is shown (Figure 9) that the correlation between conductivity and COD is practically inexistent (Koivula 2014) and can lead to inappropriate use of washing water. (Bede-Miller & Van Fleet 2014; Andersson *et al.* 2014)

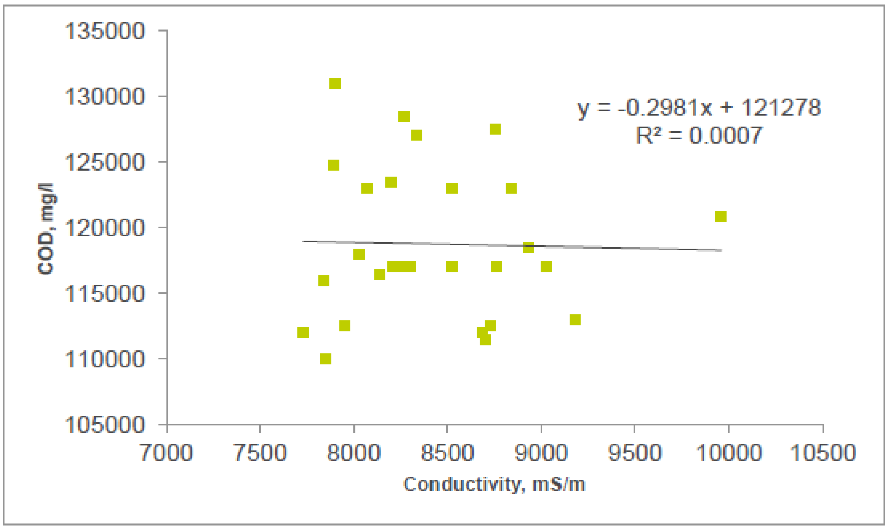


Figure 9 Relation of conductivity and COD (Koivula 2014)

Real time total dissolved solids content measurement with refractometers in any liquid medium is based on measuring the Refractive index (nD) of a solution. Refractive index is medium, temperature and wavelength dependent velocity of light in liquid phase. It is also dependent on wavelength, but the dependency can be blocked by using monochromatic light source. The measurement of refractive index is based on lights tendency to travel slower in medium than in vacuum. (Kopra *et al.* 2012; Kopra 2015)

Dissolved solids measured by refractometers correlate quite well with laboratory tests. As seen on figure 10, different wood species have different correlations. This is supposed to result from different lignin content depending on the wood type and calibration of the refractometers should thereby be done according to the species used. (Kopra 2015)

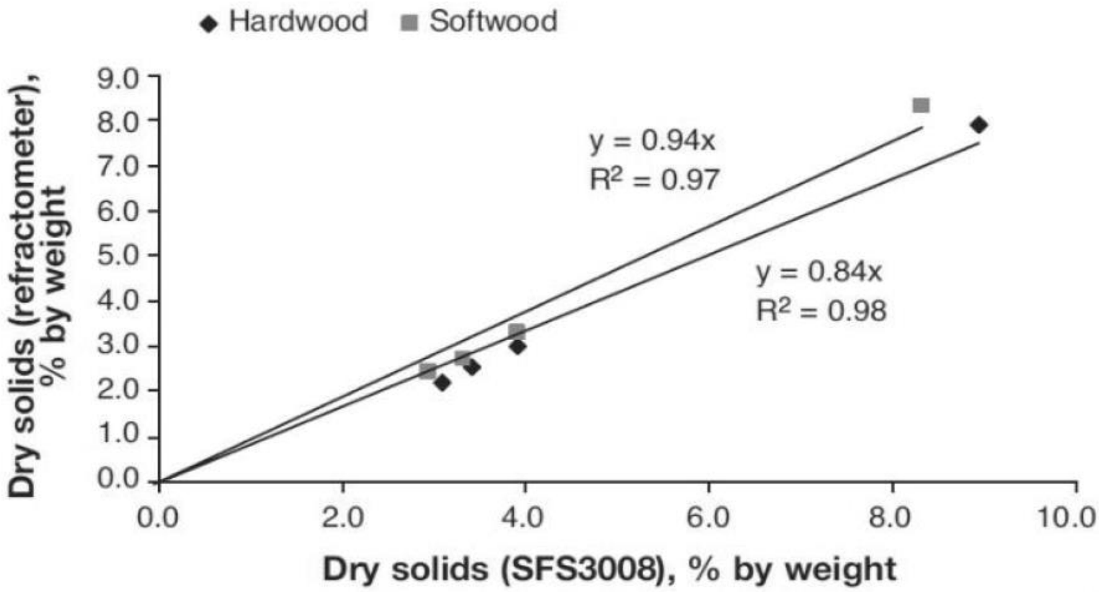


Figure 10 Hardwood and softwood dry solids content correlation with different measurements. (Kopra 2015)

Light has tendency to change direction when it meets interface of optically different density substance. Concentration is related to the critical angle, where light cannot enter the substance anymore and reflects from the surface. Light from the source is directed to the interface at different angles and at concentration related angle the rays are reflected. This is called the critical angle of refraction (figure 11) which can be seen as the dark edge in the optical image. (K-Patents 2015)

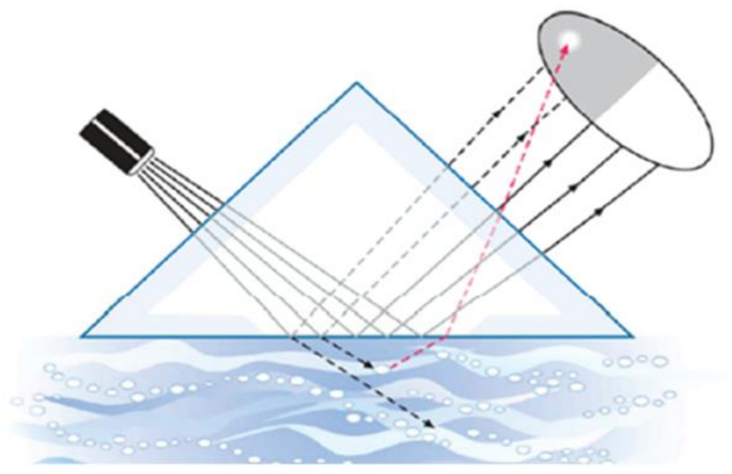


Figure 11 Principle of refractive index measurement. Light reflected from a solid object, such as fiber does not affect the measurement. (Kopra 2015)

The reflected light is collected by a CCD camera that converts the optical image into visual chart (figure 12). The critical angle of refraction or the shadow edge can now be seen as a steep drop in the image. Visual presentation is far more understandable than just a numeric value of refractive index. (Kopra 2015)

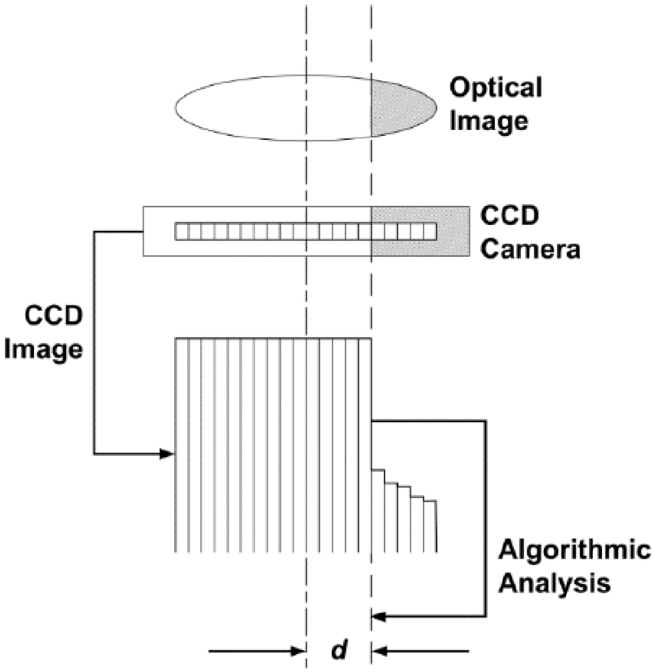


Figure 12 Optical image detection and conversion. (Kopra 2015)

Accuracy of the measurement is quite good, as it is not interfered by air bubbles, particles, or temperature changes, which all can occur in process. According to Kopra 2015, the accuracy was ± 0,0001 in the refractive index. He found also in his studies that one per cent of concentration correspondents to 0,002 in refractive index. The actual effect of concentration to refractive index is somewhat solution dependent, but as a thumb rule the previous applies. Measurement has also temperature dependence, as one centigrade correspondents to 0,05 % change in concentration. (Kopra 2015)

3 ECONOMIC VIEWPOINTS

There are several cost benefits in optimizing the usage of wash water usage and the whole washing stage. Not only does it make operating the fiber line and the whole mill easier, it also reduces the unit costs of produced pulp ton. In other words, saves a lot of money. Three most important factors economically observing are evaporation costs, chemical costs, including make-up and bleaching chemicals and costs from pumping and heating. Fourth would be decreased downtime of the brown stock washing stage due to operational errors, but this would be quite hard to evaluate.

3.1 Evaporation

In order to make black liquor suitable for energy production by burning it, the excess water has to be removed by evaporation. Solids content in recovery boiler feed is desirably 70 - 80 % and black liquor leaving the brown stock washing has solid content of 15 %. Temperature of the liquor entering the evaporation plant is 80 to 90 °C, so it has to be heated first into evaporation temperature. As flow rates are large, this requires a lot of energy. (Gullichsen & Fogelholm 2000)

Black liquor contains water and dissolved dry solids. Dry solids are divided to inorganic and organic components. Inorganic components are mainly cooking chemicals and other inert substances, where organic substances are mostly lignin in its many fractions. Organic material covers approximately 60 % of total black liquor dry solids. (Gullichsen & Fogelholm 2000)

Evaporation plant is based on the principle of separating water from nonvolatile components in black liquor as heat forces the water to evaporate. Current trend of lowering the water usage in washing stage and thereby increasing the dry solids content in black liquor entering and exiting the evaporation plant can increase the economy and capacity of evaporation plant and lead to better operation and lower emissions in recovery boiler. (Gullichsen & Fogelholm 2000)

Evaporation is usually done in series of evaporators. As seen on table 1, steam economy in multiple stage evaporation is better and specific heat comsumption lower. Three evaporators in series, for example has three times better steam economy than a sigle evaporator. (Gullichsen & Fogelholm 2000)

Table 1 Energy required for black liquor evaporation and steam economy (Gullichsen & Fogelholm 2000)

Number of stages	Steam economy, ton H_2O/ton steam	Specific heat consumption, MJ/ton H_2O
4	3.7-3.6	630-650
5	4.3-4.1	550-570
6	5.1-4.9	460-480
7	6.2-5.9	390-400

So in total, every excess ton of water entering evaporation plant requires approximately 470 MJ of energy to evaporate. There is roughly said a lot of energy used for evaporating excess water, which could otherwise be used to production of electricity. So by optimizing brown stock washing stage shower water usage and implementing the energy for electricity production unit costs of pulp ton could be decreased. (Gullichsen & Fogelholm 2000)

The effect of wash water usage to evaporation plant can also be calculated from the following equations: (Compton 1997)

$$S = \left(\frac{1-\phi_{in}}{\phi_{out}} + DF \right) * 1000 \qquad (6)$$

Where	S	Shower flow
	ϕ_{in}	Consistency of pulp in to washing stage
	ϕ_{out}	Consistency of pulp out of the washing stage
	DF	Dilution factor

$$Evap = S - \frac{TDS_{evap}}{\phi_{evap}} \tag{7}$$

Where	Evap	Evaporated water BDt
	TDS_{evap}	Total dissolved solids to evaporation
	ϕ_{evap}	Concentration after evaporation

3.2 Bleaching chemicals

Optimization of wash water usage could have significant effect on bleaching chemical consumption. Conventional way of operating washing stage leads to alternating wash loss and composition of pulp suspension. In optimal process conditions pulp suspension entering the bleaching stage contains only separate fibers and clean liquid where fibers are suspended and bleaching chemicals would react only with intra- and interfiber lignin. (Gullichsen & Fogelholm 2000; Kopra 2015)

This is unfortunately far from truth in real processes as washing result is never 100 % effective and free liquid among the fibers contains a lot of bleaching chemical consumptive matter, mostly dissolved lignin. In addition, the concentration of different substances in free liquor tends to vary as washing result fluctuates.

This inevitably leads to fluctuations in bleaching stage, inappropriate usage of bleaching chemicals and greater effluent load. Controls at bleaching stage are, due to long reactor delays, rather slow and inefficient washing results in excess chemical usage over time. Thereby controlled and stable outcome from the washing stage promotes more accurate controlling of bleaching stage, wash water usage and chemical feed.

3.3 Pumping and heating energy

Wash water fed to washing stage has to be heated and transported to washers and pumped finally to evaporation plant. All excess liquid requires extra energy for transportation beginning from the fresh water plant. In optimal situations washers use only minimum amount of washing water to get sufficient washing result. In many cases this is not possible and both pumping and heating costs increase.

Heating energy is also related to brown stock washing water usage. Wash water temperature should be high enough to lower the viscosity of liquor. Lower viscosity equals better liquor flow through the pulp mat and result ultimately in better displacement.

4 SUMMARY OF LITERATURE PART

Brown stock washing efficiency can be promoted with online dissolved solids measurements and precise dilution factor control. According to several researches done in washing optimization, effect of total dry solids monitoring and thereby adjusting the washing line accordingly is undeniable. As conductivity measures only the inorganic fraction of the pulp suspension, refractometric measurement of TDS is needed to describe the chemical state of the process more precisely.

The possibility to adjust washer parameters in real time with online measurements reduces the time gap when reacting to process fluctuations and problems. Dissolved solids amount alter the refraction angle of liquid and can easily be measured with online refractive index measurement devices. Also the accuracy of the measurements is good enough to be used as a trusted operational parameter in very demanding process conditions. This leads to increased effectiveness of the washer and lowered washing loss. Stabilized process conditions also enable easier operation of the whole washing line and to better and more consistent quality of the product.

Good washing efficiency and the minimization of washing loss minimizes evaporational load, maximizes the oxygen delignification stage functionality and kappa reduction as well as reduces the need of bleaching chemicals and environmental load.

Higher dry solids content from brown stock washing lowers the need of process steam for evaporation and provides better energy economy for the whole mill. Yearly savings can be substantial, if lowered steam demand can be utilized to electricity production. Another cost benefit is the decreased bleaching chemical cost per ton.

5 PULP MILL PRESENTATION

Kaukas pulp mill is located in the south-east of Finland with capacity of 750 000 tons of bleached pulp per year. 330 000 tons of the total production is hardwood pulp and 420 000 tons of softwood pulp. The mill has long traditions in the region and 2015 the integrate grew bigger as the new biodiesel factory started at springtime. Kaukas pulp mill has two separate fiberlines for hard- and softwood, 12 digester Super-Batch cooking system and sawdust digester for hardwood fiberline. (UPM Kaukas 2015)

Washing stage begins, when pulp suspension is fed from stabilization tank to pre-thickener. Pulp flow consistency is maintained stable with liquor feed to maximize the performance of the pre-thickener and to minimize the consistency variation after it. It is crucial for washer performance that incoming consistency is stable. Pre-thickener increases the consistency of pulp flow from 4 % to 5,4 % and extracts a portion of the dirtiest liquor.

After the pre-thickener pulp is fed to 2 brown stock washers. First brown stock washers are referred later as DD1, DD2. Dirty liquor is displaced in multiple washing stages with cleaner liquor. Washer is normally controlled by setting the feed pressure to desired level by operator, drum torque and rotation velocity are not controlled and the can vary greatly according to pulp properties. Performance of the washer is monitored by setting the wash water amount so, that conductivity is maintained at low level. Production rate increases the pulp flow to washers. When production is increased, either drum rotational speed or drum torque has to be increased to correspond the production.

After the washers pulp is fed to oxygen bleaching stage which consists of feed tank, MC-pump, chemical feeds and two reaction towers. It takes around 90 minutes for the pulp to pass the oxygen stage and reach the O_2 washer. Oxygen and caustic feeds are controlled by production rate and target kappa number. Inlet kappa before the oxygen stage is 18 and it is lowered to 13 – 14 at the two serial reactors.

Last DD-washer at washing stage is the oxygen stage washer, referred as DD3. This is the point where water circulation brakes, and wash loss to subsequent stages is permanent.

Cooking chemicals and lignin has to be sufficiently salvaged in order to cut both make-up and bleaching chemical costs. Proper operation of the oxygen stage washer is crucial to the efficiency of the whole washing stage.

Pulp from washing stage is then discharged at 90 °C temperature to storage tower 1 (SMT-1), which operates as hot acid stage for HeXA removal. Sulfuric acid is fed through MC-pump to pulp line to lower the pH to 3,5. Pulp stays at the A-stage for 2-3 hours and is then fed to sorting stage and bleaching.

As wash water amount is operator controlled, dilution factor of the washer is not controlled and can vary greatly. This leads to fluctuation in outlet consistency, washing result and later in chemical consumption.

6 EXPERIMENTAL PHASE

Before the actual trial period, the operation and functionality of the different washers drum torque controls and dilution factor controls were tested. To get reliable information of the functionality tests were done individually by turning on a single feature of the upper level control and evaluating the performance with the operators.

There had been problems with the control previously when process situations had rapidly changed and the rather slow reactions of the upper level controls could not respond. It had been somewhat normal in alternating process situation to turn off the controls and respond to changes manually. This had caused reasonable doubt for the upper level control usability and it was turned off quite easily and left unused.

Before trial runs were made, operators trust for the system was gained by operating the line with controls on and fixing the problems that were found. After the functionality of the upper level control was enhanced and operators trust gained, the trial runs were made. It was essential to do this project in this particular order, as operators had really bad experiences from the previous trials.

Reasons for the stiffness in case of dynamically moving process were studied and changes according to results were made to enhance the functionality. The torque control of oxygen stage washer was the first one to be turned on, as it is the last point were cooking chemicals can be salvaged and because it determines the COD load to bleaching.

The dilution factor control of oxygen stage washer was introduced then to find out the filtration capacity of the washer at different process situations. Reason for this was to determine if it is possible to operate the washing stage while the by-pass valve remains completely closed. Operating the washing stage through oxygen stage washer would lead to optimum usage of wash water and precise dilution factor control.

Dilution factor control of DD1 and DD2 was utilized last, as the dilution factor for the washers originates from oxygen stage washer filtrate tank level. The changes made are discussed more in the results section.

Experimental phase was done in the period of 8 weeks. During the trial period upper level controls were maintained on as much as possible. Also the performance of the equipment and upper level control was tested by alternating different variables in the line and by measuring the changes in performance of the washing stage.

Trial runs included DD1 and DD2 inlet consistency, dilution factor, drum torque and wash water temperature tests. Results were evaluated by measuring the washing loss of washing stage from oxygen stage washer and with several other measurements. These are discussed also at the results section.

6.1 Upper level control

The upper level operational system for the hardwood fiberline was build 2014 in co-operation with Metso. Operational philosophy is based on adjustment of dilution factor of the washing stage and rotational control of each washer independently. Principle idea is that each moment delivered wash water per pulp ton is equal and washing result remains constant.

Upper level control is divided to 3 different levels that control the operation of washing stage according to the chemical state of the process. Fundamental idea of different operation levels of the control are presented in figure 13.

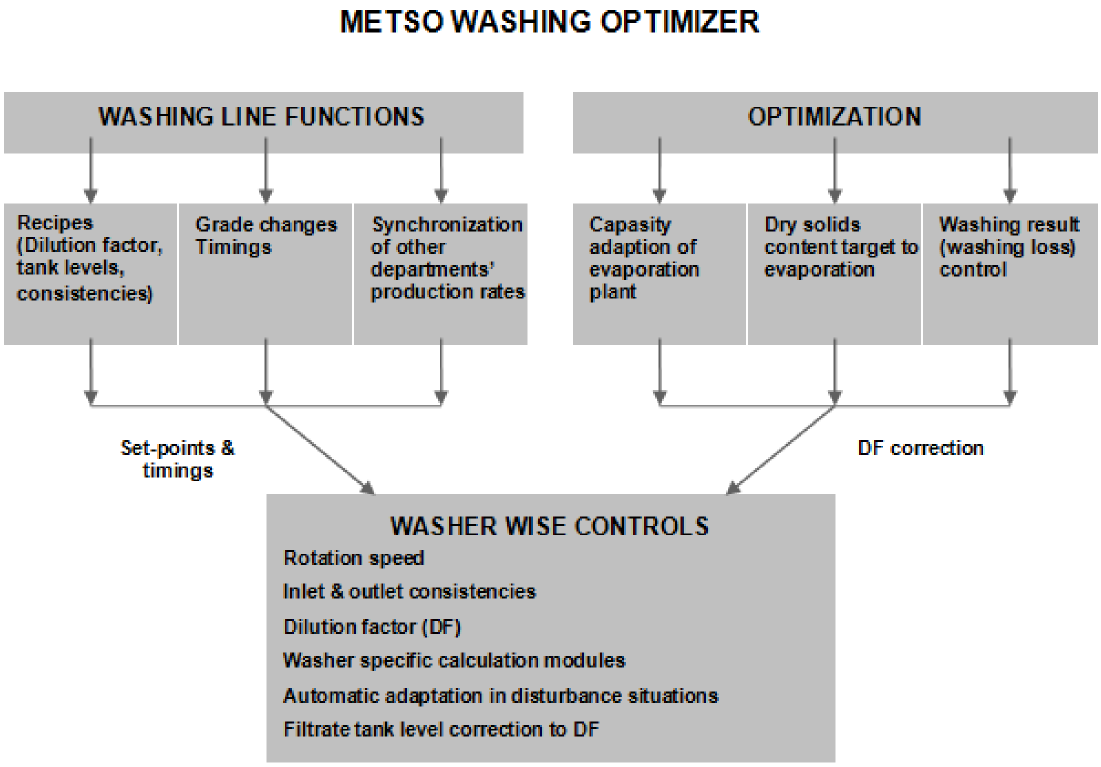


Figure 13 Upper level control operation chart. (Metso 2014)

At the lowest level are washer specific operations, such as consistency, dilution, rotation speed and feed pressure controls. These are the ground level operations and the most important factors affecting the whole washing line performance. In order to utilize proper washing line optimization, it is essential to optimize washer performance first. Precise function of every pump, valve and metering affecting washer performance is critical to upper stage optimizing. (Kapanen & Kuusisto 2002)

On the mediate control level are the washing line operation parameters and optimization parameters. Operation parameters consist of recipes, timings and information about other departments of the mill. Optimization parameters on the other hand take care of the material balances, adapt the washing water usage according to washing loss and filtrate dry solids content determinations. (Kapanen & Kuusisto 2002)

The highest level of control is to determine the key parameters for the whole washing line. Lower level functions are defined on the upmost stage of controls by operators. (Kapanen & Kuusisto 2002)

The main operation window for Kaukas hardwood washing stage (figure 14) displays the most important information of the washing stage to operators. From this page it is possible to get a good picture of the whole process at one glance. Washing stage with its most important unit operations, piping and operational parameters are presented visually as well as individual washers own operational boxes. These are presented in the circulated area 1 and consist of dilution factor, E-value and rotational torque/feed pressure control indicator.

Area 2 represents the different dilution factor correction values that are based on the process conditions at the moment, and the total correction factor on the right end of the circulated area. Correction factors are based on oxygen tank filtrate level, conductivity, total dry solids and production rate. There is also an option for evaporation plant load, but it is not used as evaporation capacity can be considered adequate.

The total correction factor is added to dilution factor set by operators and this increases or decreases the wash water amount in the washers accordingly.

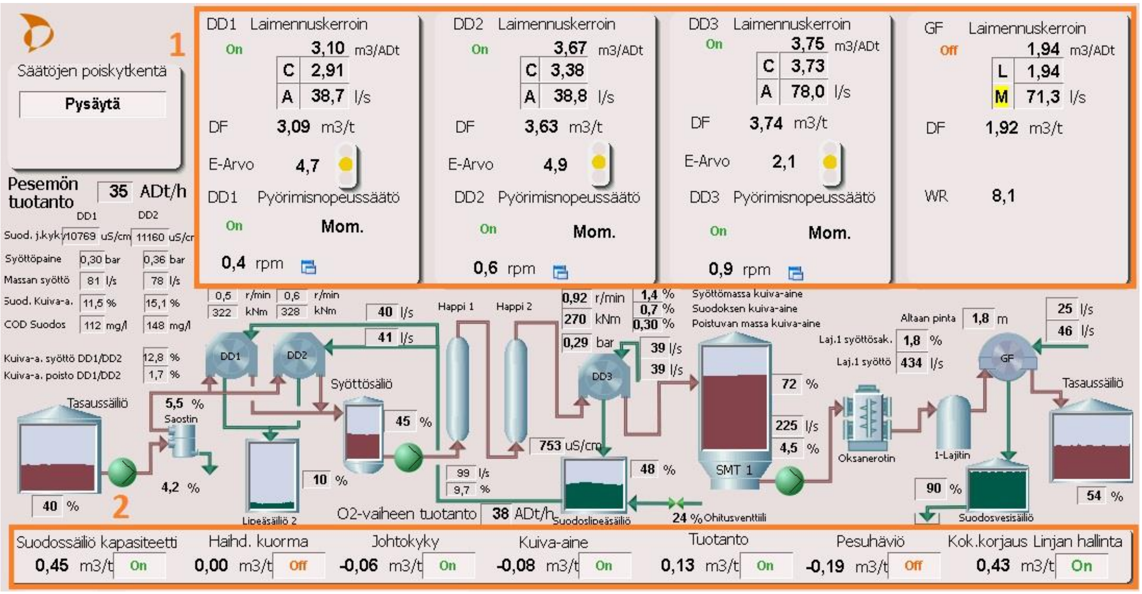
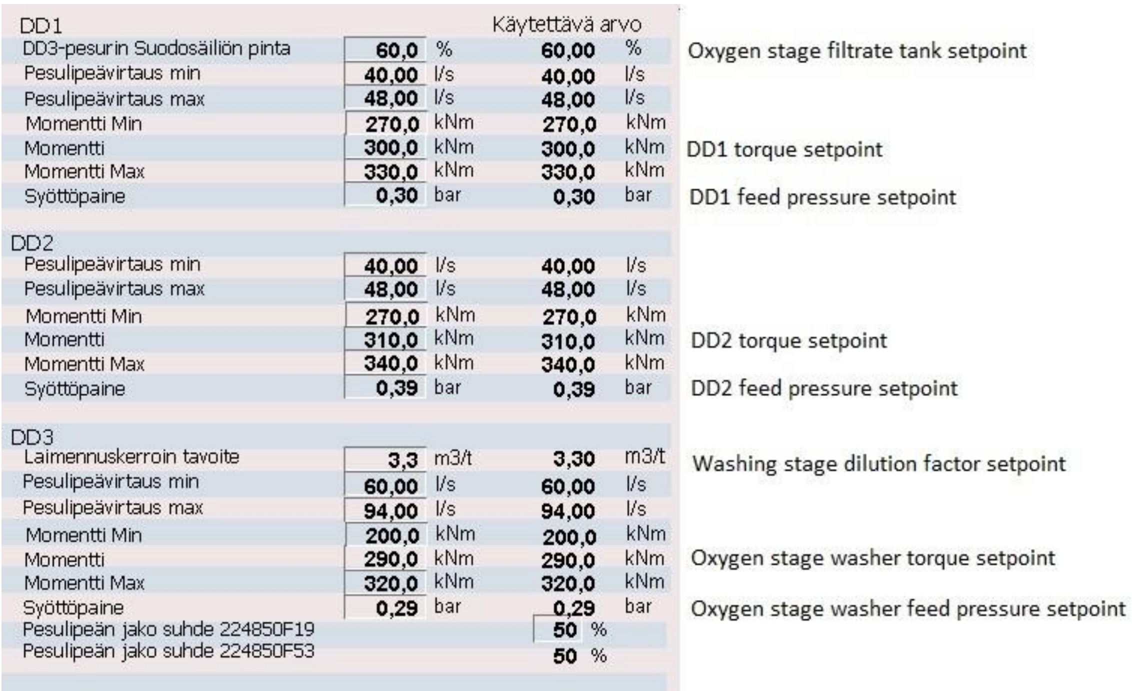


Figure 14 Main operating window for upper level control.

Under the main operating window are all the key parameters for the washing stage (figure 15). This is the most important page for the operators to understand and how different parameters affect to washing stage operation. Parameters include setpoints and operational limits fo oxygen stage filtrate tank level, wash water amounts, drum torque, feed pressure and dilution factor. Dilution factor is only presented in the oxygen stage washer (DD3) as it is meant to determine the dilution factor for the whole washing stage.



DD1			Käytettävä arvo		
DD3-pesurin Suodosäiliön pinta	60,0	%	60,00	%	Oxygen stage filtrate tank setpoint
Pesulipeävirtaus min	40,00	l/s	40,00	l/s	
Pesulipeävirtaus max	48,00	l/s	48,00	l/s	
Momentti Min	270,0	kNm	270,0	kNm	
Momentti	300,0	kNm	300,0	kNm	DD1 torque setpoint
Momentti Max	330,0	kNm	330,0	kNm	
Syöttöpaine	0,30	bar	0,30	bar	DD1 feed pressure setpoint
DD2					
Pesulipeävirtaus min	40,00	l/s	40,00	l/s	
Pesulipeävirtaus max	48,00	l/s	48,00	l/s	
Momentti Min	270,0	kNm	270,0	kNm	
Momentti	310,0	kNm	310,0	kNm	DD2 torque setpoint
Momentti Max	340,0	kNm	340,0	kNm	
Syöttöpaine	0,39	bar	0,39	bar	DD2 feed pressure setpoint
DD3					
Laimennuskerroin tavoite	3,3	m3/t	3,30	m3/t	Washing stage dilution factor setpoint
Pesulipeävirtaus min	60,00	l/s	60,00	l/s	
Pesulipeävirtaus max	94,00	l/s	94,00	l/s	
Momentti Min	200,0	kNm	200,0	kNm	
Momentti	290,0	kNm	290,0	kNm	Oxygen stage washer torque setpoint
Momentti Max	320,0	kNm	320,0	kNm	
Syöttöpaine	0,29	bar	0,29	bar	Oxygen stage washer feed pressure setpoint
Pesulipeän jako suhde 224850F19			50	%	
Pesulipeän jako suhde 224850F53			50	%	

Figure 15 Upper level control setpoints and operating limits. The most important are explained on the right.

As said, there is an operational indication box for each washer on the main window (figure 16). From this operators can see the current dilution factor, which is the total dilution factor with corrections, the washer performance indicating E-value, which is equipped with traffic light for easy understanding, drum rotational control torque/feed pressure indicator and drum rotating speed. From these values it is easy to make quick analyze of the washers state at the moment.

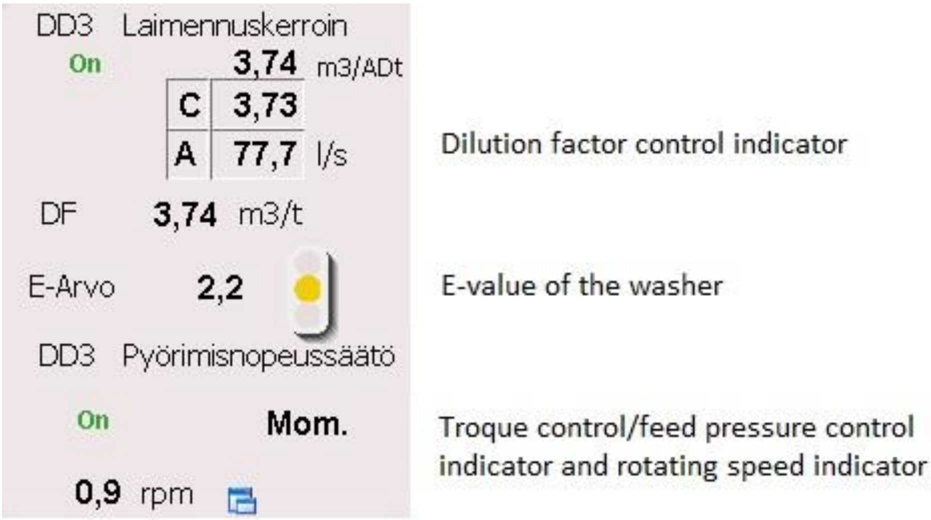


Figure 16 Upper level control main indicator window for oxygen stage washer

For every washer there is a setpoint and limits for feed pressure, drum torque and wash water amount. On figure 17 oxygen stage washer feed pressure and drum torque controls are presented in circulated area 1. This indicates the real time situation at the washer and can be somewhat different than the operator defined setpoint. As properties of pulp may vary greatly in short period of time, washer has to react by changing the torque setpoint according to the situation. This is called the floating setpoint.

Floating setpoint controls the drum torque by lowering the torque setpoint if feed pressure risis too many times higher than feed pressure limits, presented in circulated area 2, allow. On contrary, if feed pressure is much lower that the setpoint, correction to torque setpoint is done to a higher level. Operating the washing stage with floating setpoint allows optimal washing result in every process situation.

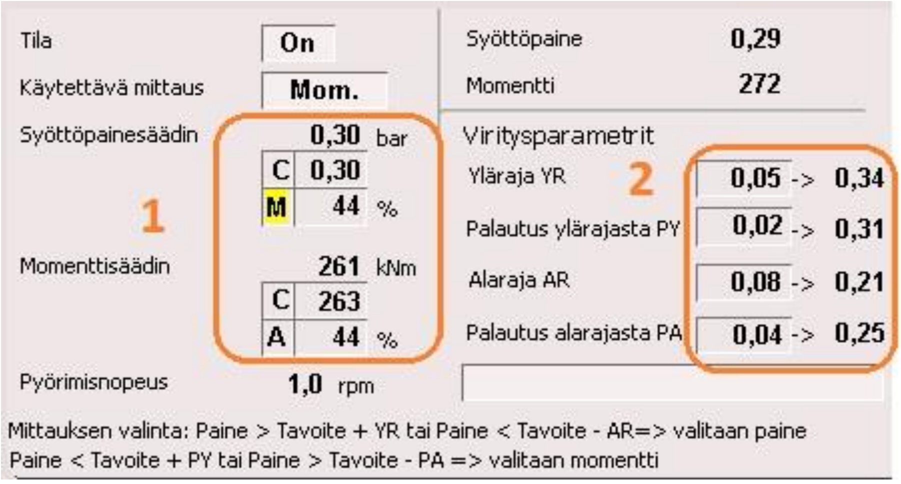


Figure 17 DD-washer operating parameters. Circled area 1 consists of the feed pressure and drum torque control and area 2 upper and lower limits for feed pressure and torque control return points.

Dilution factor corrections are made according to parameters presented in figure 18. Circulated area 1 on the picture presents the filtrate tank difference to setpoint and dilution factor correction made according to parameters on the left side. By changing the parameters, filtrate tank level control can be made more agressive. Area 2 presents the conductivity correction, area 3 total dry solids content. Conductivity and total dry solids content corrections are calculated by the weighted average of different process points and correction are made accordingly. Most important process points are DD1 and DD2 discharge, oxygen stage washer inlet and oxygen stage washer discharge.

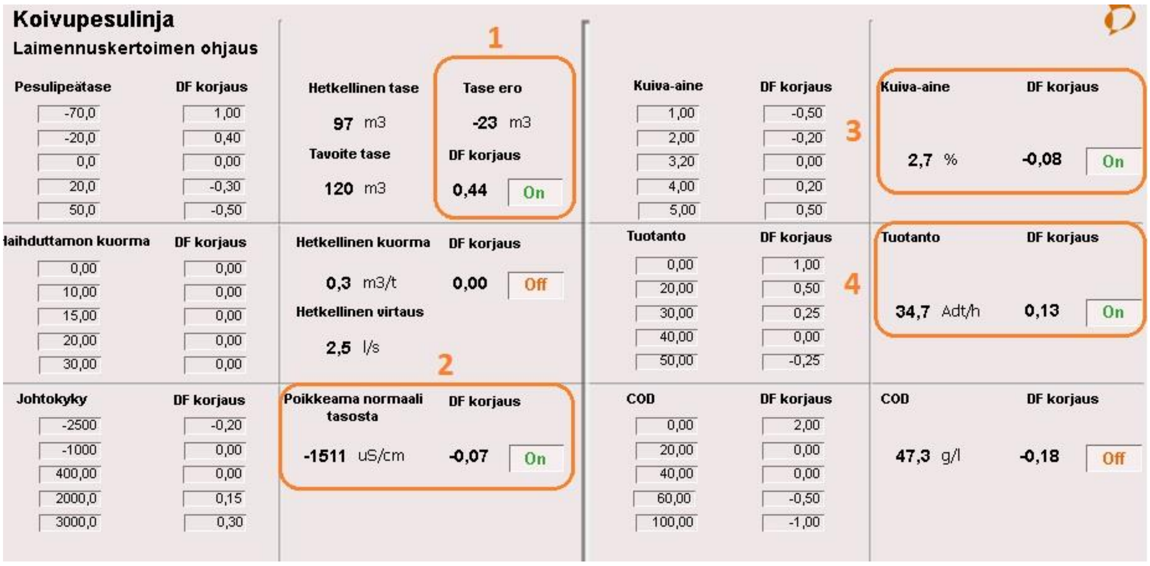


Figure 18 Dilution factor correction factors parameters. 1: filtrate tank level, 2: conductivity level, 3: TDS level, 4: production level.

6.2 Refractometers

There are 8 refractometers installed in Kaukas hardwood fiberline (figure 19). The refractometer installation sites are listed below on table 2. Refractometers in Kaukas pulp mill are PR-23 type and provided by K-patents. Installations are made in pulp suspension lines and entering and exiting wash liquor lines. Those installed in the washer filtrate lines are equipped with additional steam lens cleaning system.

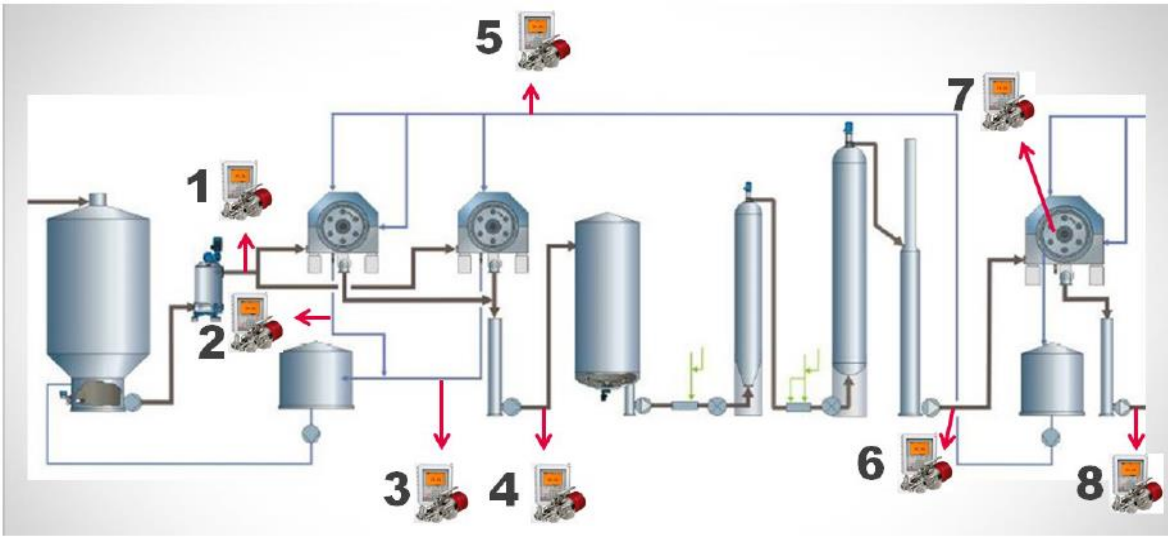


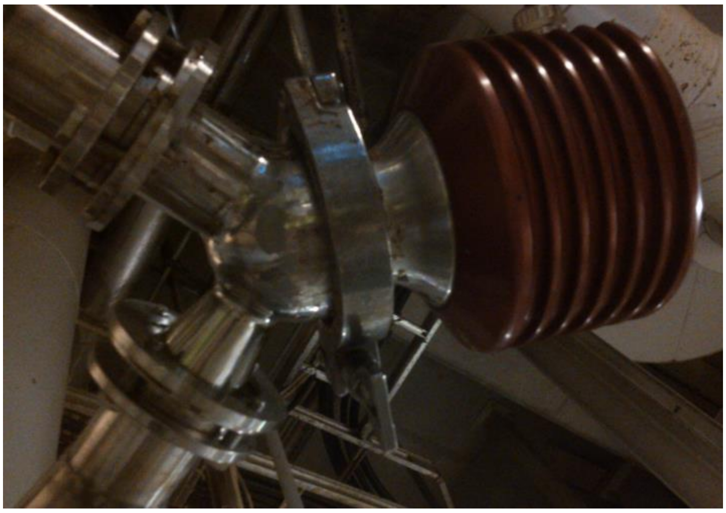
Figure 19 Refractometer installation in the fiberline 1 (Koivula 2014)

Table 2 Process equipment installation locations

Refractometer no.	Process site
1	Pulp feed to DD1 and DD2
2	Filtrate from DD1
3	Filtrate from DD2
4	Pulp feed to oxygen stage
5	Wash liquor DD1 and DD2
6	Pulp feed to oxygen stage washer
7	Oxygen stage washer vacuum tank
8	Pulp to bleaching

The two first brown stock washers DD1 and DD2 as well as the oxygen stage washer DD3 have real time refractive index measurements at the pulp inlet and outlet and in washers filtrate outlet. This is a simple and short response time way of monitoring washing efficiency. Refractometers are proven to be able to operate at challenging conditions at high temperature, high alkalinity and pressure. (K-patents 2014; Kopra 2015) Picture 2 presents the oxygen stage washer filtrate tank measurement, which determines the TDS from DD1 and DD2 washing liquor. Picture 3 is taken from DD3 vacuum tank measurement before the installation of steam wash unit.

Picture 2 Refractive index measurement in oxygen delignification washer filtrate tank, also referred as DD1 and DD2 wash liquor. Steam wash is installed on the right side of the measurement device.



Picture 3 Measurement in oxygen stage washer vacuum tank. Steam wash unit was installed to prevent contaminations to the lens, especially during process disturbances.

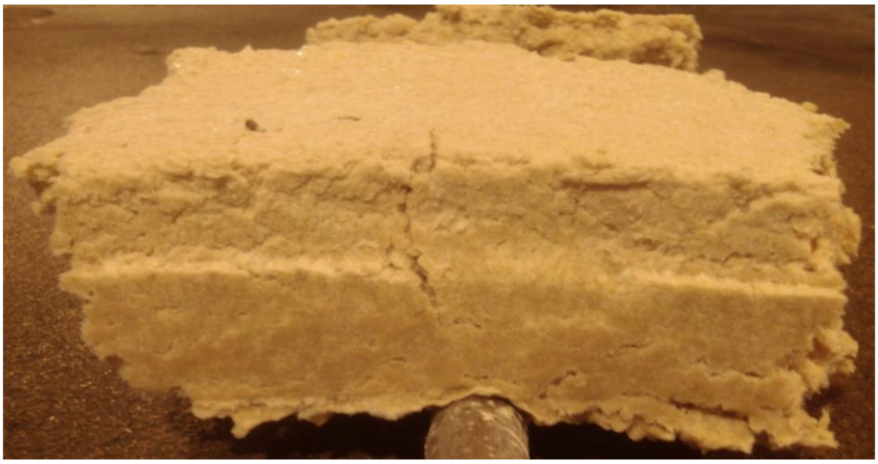
6.3 Analytical methods

Performance of the upper level control and the whole washing stage were evaluated both online measurements and laboratory analyzes. Trial runs included measurements of consistency of pulp suspension, conductivity, COD and TDS of filtrates and washing loss measured represented as kgCOD/ADt.

Performance of a single washer was evaluated by taking samples from the washers cake discharge (picture 4). All the samples including DD1, DD2 and oxygen stage washer were performed this way as it represents the true performance of the washer before any dilutive liquid is added to the pulp. For carry-over tests liquid was squeezed out of the cake with special tool made for the purpose.

All the washing liquid used in washing stage is secondary condensate. The quality of secondary condensate was measured during both reference and trial period. Quality was evaluated by measuring TDS, conductivity and COD.

Measurement of pulp suspension COD represented as mg/l was done using Macherey-Nagel Nanocolor 500d and vario 3 according to ISO 15705. Conductivity of different filtrates was determined by using Mettler Toledo SevenEasy and total dry solids content according to ISO 638:2008.



Picture 4 Sample at oxygen stage washer cake discharge

7 RESULTS AND DISCUSSION

A series of trial runs were made to evaluate the functionality of the upper level control and performance of the washing stage. In August washing stage was controlled mostly by upper level control. Torque controls were used in all of washers 73 %, dilution factor control for oxygen stage washer 73 % and dilution factor for DD1 and DD2 25 % of the whole month. DD1 and DD2 dilution factor was not utilized earlier due to problems with data transfer in the operating system.

On September and October the functionality of the washing stage control was improved more and utilization percentage reached more than 90 % level. So, it can be stated that upper level control was used all the time the washing stage was on normal operation, excluding production stops resulting from other departments.

Total effect of the upper level was determined by comparing the dry solids content and COD washing loss before and after the utilization of the control. As seen on figure 20, the efficiency of the washing increased and total dry solids measured from the oxygen stage washer cake discharge dropped an average of 27 % during the optimization of the washing stage.

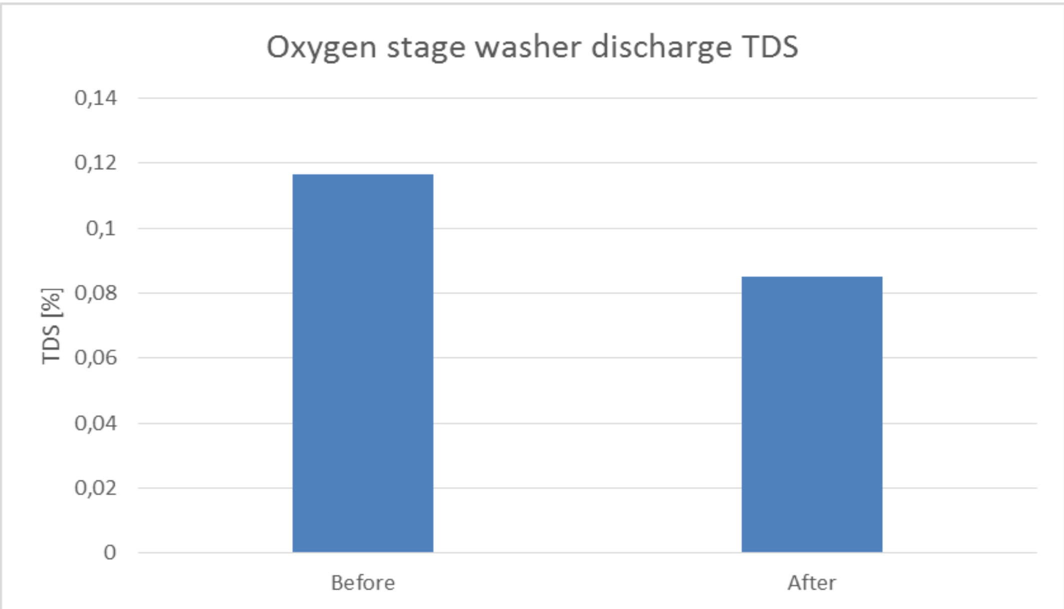


Figure 20 Decrease of total dry solids in cake discharge of oxygen stage washer, analyzed in laboratory before and after the utilization of upper level control.

Organic load to bleaching, which can be seen to consist mostly of lignin, was evaluated by determination of COD load per ton of pulp. While washing stage was operated traditionally, organic load was quite large. Excess organic matter caused inappropriate usage of bleaching chemicals and promoted formation of environmentally hazardous compounds.

Upper level control provided needed stability to washing stage, optimal usage of washing water and precise functionality of process equipment. This could be seen as reduced COD load. Represented as kgCOD/ADt (figure 21), total washing loss dropped 32 % during the trial runs.

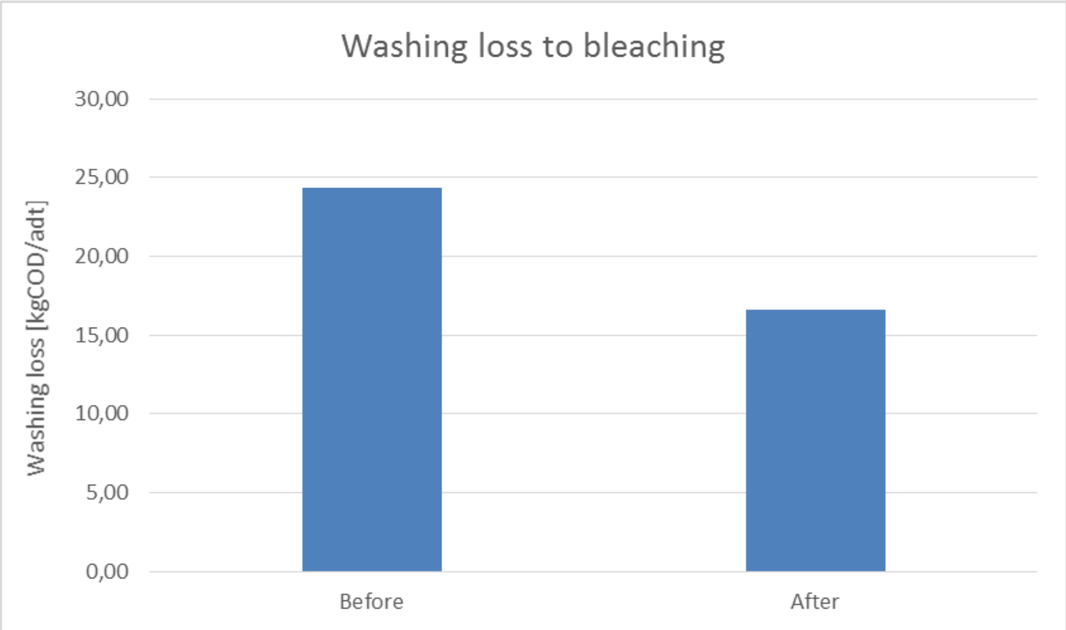
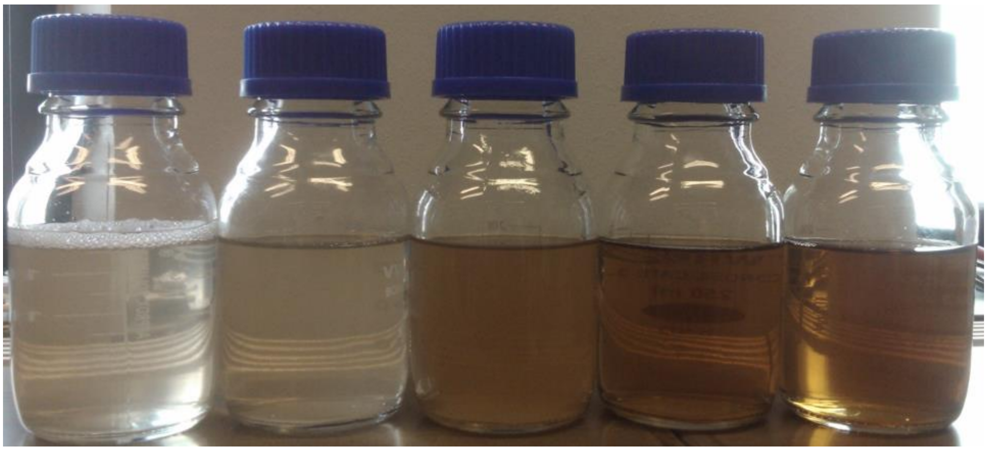


Figure 21 Washing loss to bleaching analyzed in laboratory before and after the utilization of upper level control, represented as kgCOD/ADt.

The quality of secondary condensate varied during the tests. Daily visual checks were made to observe, if there should be any possible problems with the quality. As seen in picture 5 in normal process conditions secondary condensate is clean and contains only a fraction of contaminant, but when evaporation plant is suffering from process difficulties, condensate purity can differ greatly.



Picture 5 The quality of secondary condensate. On the left are samples when secondary condensate quality is good, and when moving to the left the quality deteriorates. Conductivity of secondary condensate analyzed in laboratory varied between 12 and 54 mS/m and COD between 1780 and 3170 mg/l.

7.1 Dilution factor

The effect of dilution factor on performance of the washing stage, evaporation plant load and consumption of bleaching chemicals as kgClO_2/ADt were tested by alternating the dilution factor while the upper level control was switched on. To be able to determine the exact dilution factor for the whole washing stage, all washing liquid would have to enter the washing stage through oxygen stage washer. Filtrate tank of O_2 washer is equipped with a by-pass line for washers filtrate tank level control purpose, but it is essential for optimizing the washing stage to keep the valve closed. To ensure precise dilution factor, trial run was conducted so that filtrate tank level was kept high and the by-pass valve was closed during the trial run.

The optimum dilution factor can be found somewhere in the middle of minimum bleaching chemical consumption and minimum load to evaporation plant. The less water is used, evaporation plant load decreases and chemical consumption increases as pulp entering the bleaching stage is dirtier, and vice versa.

As more liquid would have to be fed to washer, it is crucial that the rotating speed of the drum could be kept as low as possible. This allows the liquid to have enough time to pass through the pulp cake. If rotation is too fast and displacement time is not long enough, liquid will be discharged with pulp and it will not be used for DD1 and DD2 washing purposes. In addition this lowers the consistency of discharged pulp and increases the carry-over.

At optimal process conditions torque of the drum is high, rotation of the drum as slow as possible and cake discharge consistency high. This ensures that displacement is at maximum level, discharged pulp is at high cleanliness and dilution factor of the washing stage is kept at optimal level.

When dilution factor control was utilized at DD1 and DD2, the dry solids content of washer filtrates rose from the average of 11,3 % to 12,8 % at dilution factor of 2,9 m^3/ADt. This means that wash water was used more precisely and the evaporated water amount decreased.

Figure 22 demonstrates the effect of dilution factor to total dry solids content of oxygen stage washer cake discharge. Increasing the dilution factor from 2,7 to 3,7 decreased the total dry solids content by 50 %, but increased the wash water flow by 13,01 l/s, which corresponds to 16,4 %. The trial run indicates, that one dilution factor unit (m^3/ADt) corresponds to 1124 m^3 of evaporated water per day and 393387 m^3 per year (350 days).

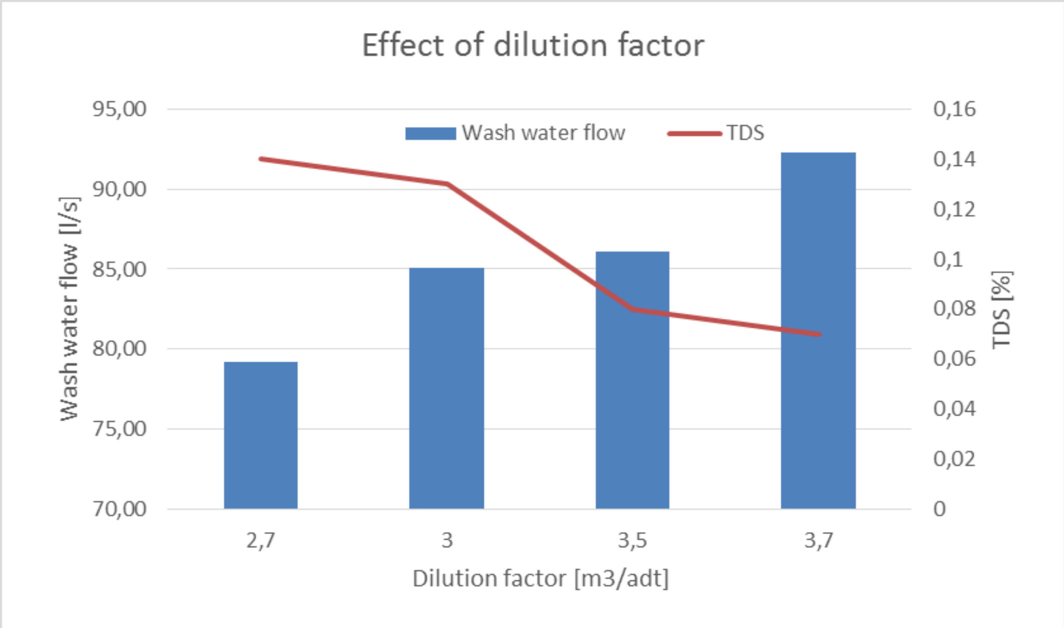


Figure 22 TDS of pulp entering bleaching. Wash water usage was calculated from DD1 and DD2 flow indicators and TDS was analyzed from a pulp sample in laboratory.

Total costs of increasing or decreasing the dilution factor by $1m^3$/adt is approximated on table 3. Results show, that redusing wash water amount has huge impact on evaporation costs. Actual savings depend highly on the process contitions, as same dilution factor cannot be utilized in all the situations.

Table 3 Effect of dilution factor on total costs. Calculations were made on 13 l/s was water reduction, energy price of 20€/MWh, steam energy content of 2,2MJ/kg and on the fact that 1 kg of water evaporated with 6 evaporators require 1/5 kg of steam.

	Energy price €/MWh	Decreased evaporation load [kg/d]	Steam saved [kg/d]	Energy saved [MJ/d]	Evaporation energy consumption [MWh/d]	Total savings [€/350d]
Dilution factor 2,7 - 3,7	20	1123964	224792,83	494544,23	137,37	961614

Organic washing represented as kgCOD/ADt, in terms of dilution factor was evaluated operating the washing line at different dilution factor levels. The by-pass valve was completely closed during the trial run, which made the determination of the dilution factor straighforward. As figure 23 shows, there is almost a linear correlation between dilution factor and washing loss in evaluated region. By increasing the dilution factor by 1 m^3/ADt, washing loss decreased 16,7 % from 18 to 15 kgCOD/ADt. From the perspective of quality, higher dilution factor results in better washing result.

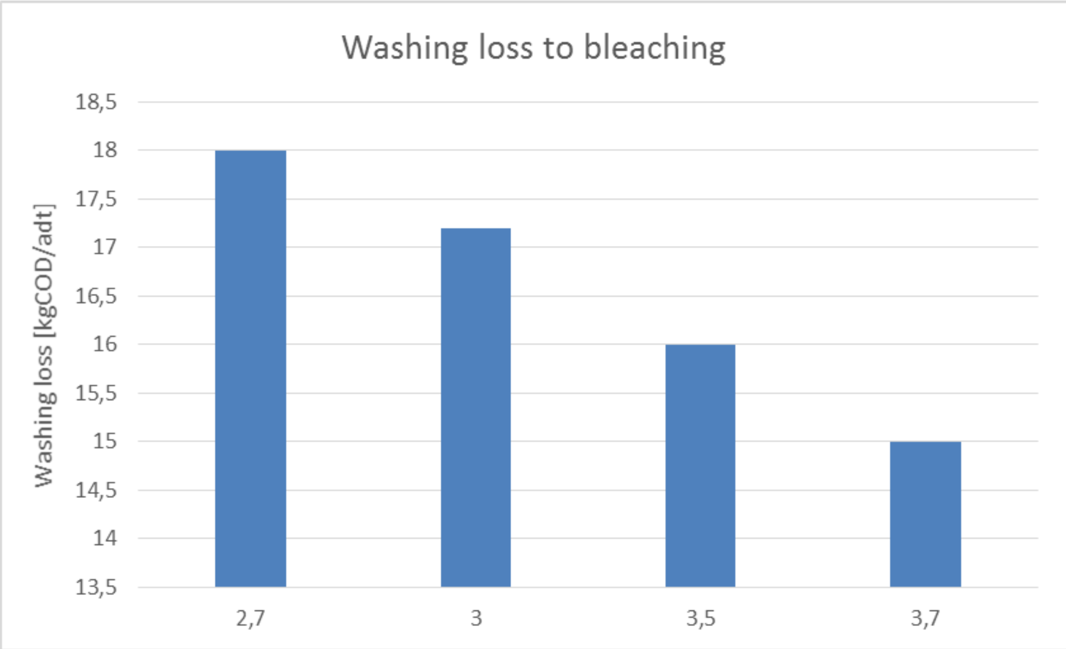


Figure 23 Organic load to bleaching analyzed from oxygen stage washer pulp sample in laboratory and represented as kgCOD/ADt.

From another perspective the effect of dilution factor is not so straight forward. When observing figure 24, it is shown that at low dilution factor levels the circulated wash water dry solids content is rather high, implicating, that wash water amount is insufficient to displace the dirty liquor and the washing result is somewhat insufficient.

Dry solids content drops, when dilution factor is increased, but starts to increase rapidly again when dilution factor is raised above 3,5. This is due to the fact, that increasing oxygen stage washer eash water amount, the upper level control increases DD1 and DD2 wash water amount likewise.

At high dilution factors DD1 and DD2 are not able to maintain sufficient penetration of washing water and some of it is carried out with the pulp. This lowers the consistency of the pulp flow to oxygen stage and increases the flow rate. Because of the increased flow rate, oxygen stage washer starts to rotate more rapidly, decreasing the displacement time and deteriorating the washing result.

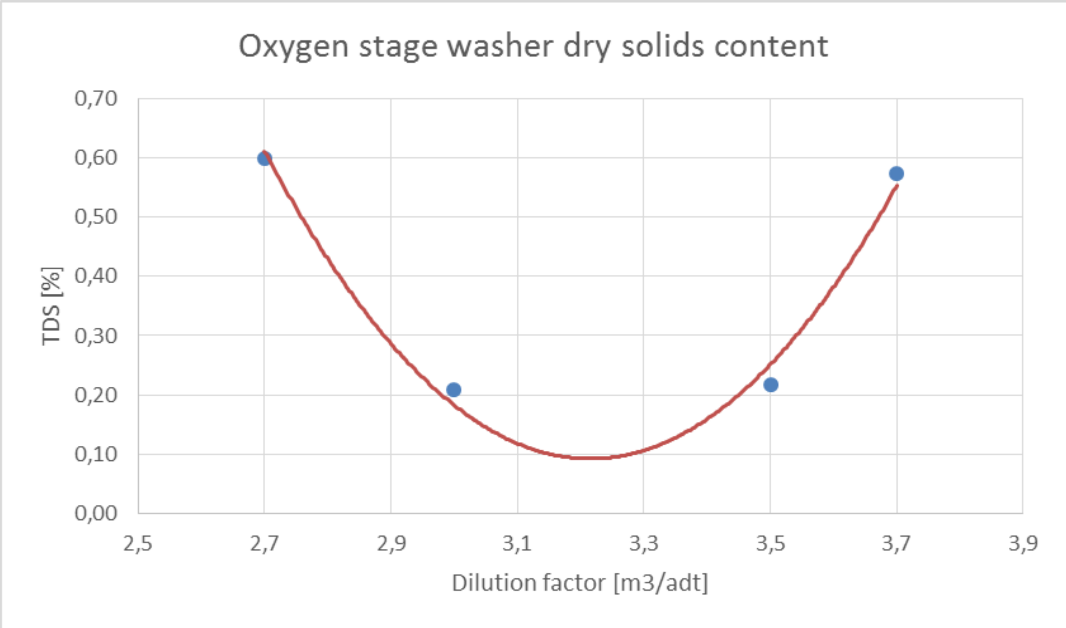


Figure 24 Dry solids content of oxygen stage washer, measured with online refractometer from the oxygen stage washer vacuum tank

Figure 25 enlightens the effect of dilution factor to pulp conductivity and COD measured from the cake discharge of oxygen stage washer. According to literature, inorganic portion of the pulp suspension is rather easy to be washed away. This can be confirmed as conductivity of the pulp decreases almost linearly as dilution factor is increased. Total reduction of conductivity was 43,4 % when dilution factor was increased from 2,7 to 3,7. Loss of cooking chemicals were determined at dilution factor of 3 and was found to be 3,48 kg$NaSO_4$/ADt. This can be considered to be at good level.

On contrary, organic portion of the washed pulp is considered to be harder to wash away. Figure 16 shows, that increasing dilution factor from 2,7 to 3,5 lowers the organic washing loss by 28,8 %, but at high dilution rates the amount starts to rise again. As organic matter, mostly lignin, needs sufficient time to be washed away it can be noted that increased liquid flow rate causes the oxygen stage washer to rotate more rapidly and cause insufficient time for washing of organics.

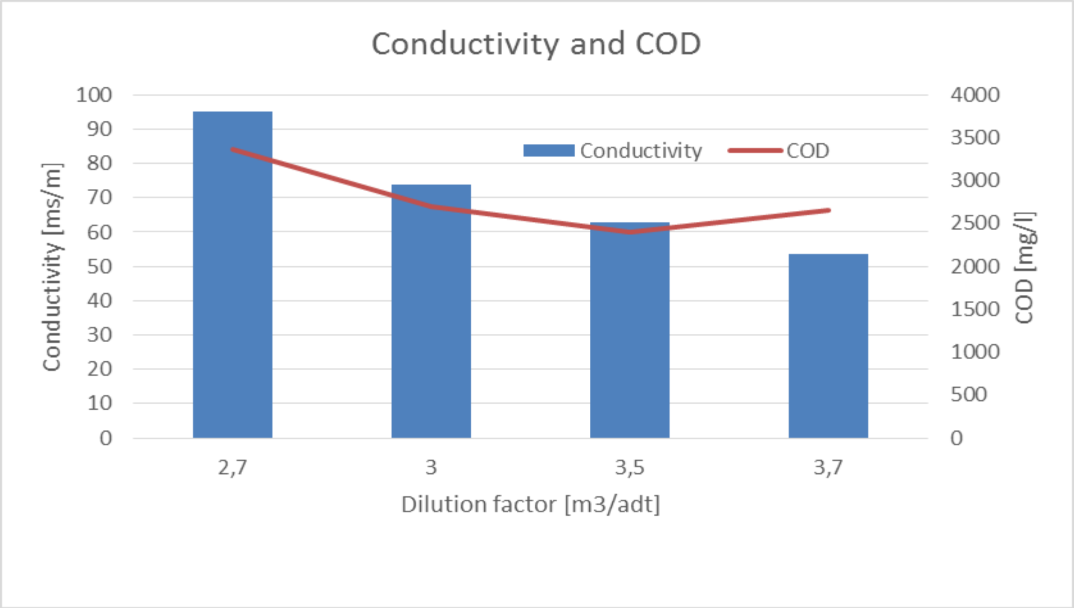


Figure 25 Conductivity and COD measured in laboratory from oxygen stage washer cake discharge.

Figure 26 illustrates the cost of heating required for rising the secondary condensate temperature from average of 63 °C to utilization temperature of 90 °C. As the figure shows, increasing the wash water flow by 1 liter at energy price of 20 €/MWh (Kauppinen 2015) increases the costs by approximately 19000 €/year. So, by closing the oxygen stage washer by-pass valve and introducing more heated wash water to washer, the heating costs rise. The situation is controversial as better utilization of wash water gives more precise control of dilution factor and better utilization of wash water. In addition must be stated, that heating costs are minimal compared to other benefits.

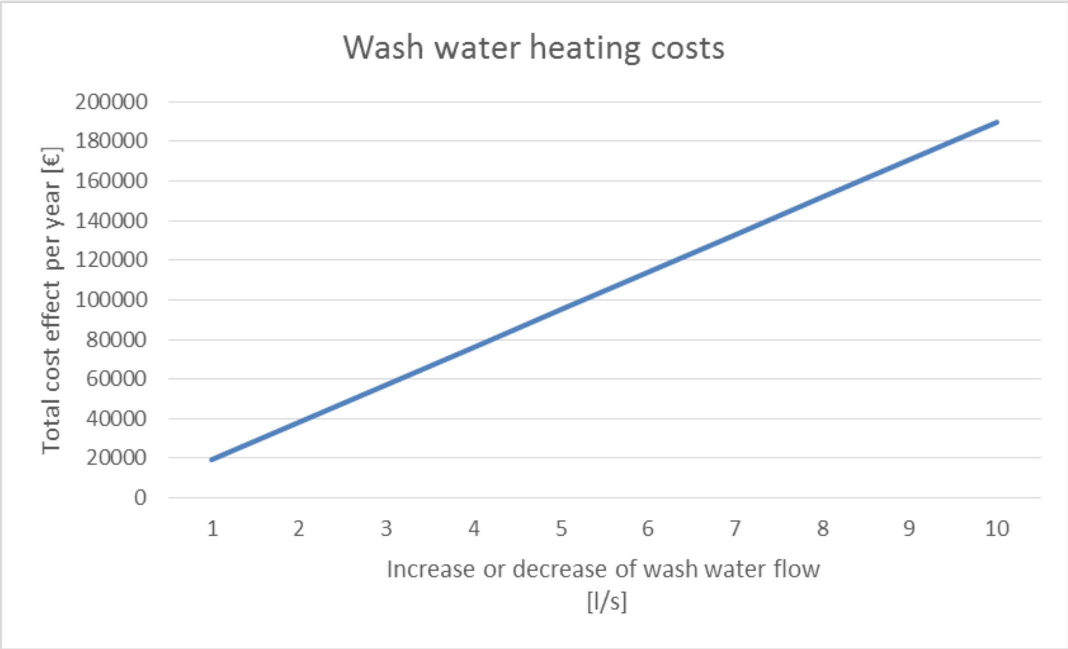


Figure 26 Total cost of increasing or decreasing wash water flow. Secondary condensate heating from 63 to 90 °C.

7.2 Drum torque

Effect of torque to washing result was tested with oxygen delignification washer. Trial run was conducted so that the floating torque set-point was turned off to maintain a specific torque level during different test levels.

Trial run was carried out using 3 different torque levels: High, medium and low. Set-points for these were 300, 250 and 190 kNm. Different torque levels were maintained as steady as possible for approximately 45 minutes to stabilize the system to this specific operational point. Data was evaluated at a time zone, where all the variables would remain as steady as possible. Thickness of the discharged cake was also measured at different torque levels.

At first, torque was set to 300 kNm and gradually lowered to a point where feed pressure dropped below 0,2 bar deteriorating the washing result completely. Results from the torque trial are presented in figures 27-29.

Chemical oxygen demand causing fragments in the pulp suspension leaving the washer was found to be highly dependent to washer torque. As torque is lowered, the drum tends to rotate faster, causing the time for displacement decrease substantially. As COD correlates mostly with hard to wash substances, such as lignin, it can be seen that setting the torque to high level is crucial for proper displacement.

As it can be seen from figure 27, increasing the oxygen delignification washer torque from 200 kNm to 300 kNm decreases the COD load to delignification by 92 %. Higher torque improves washing result and washing liquor circulation. This results in cleaner and higher consistency pulp out of the washer.

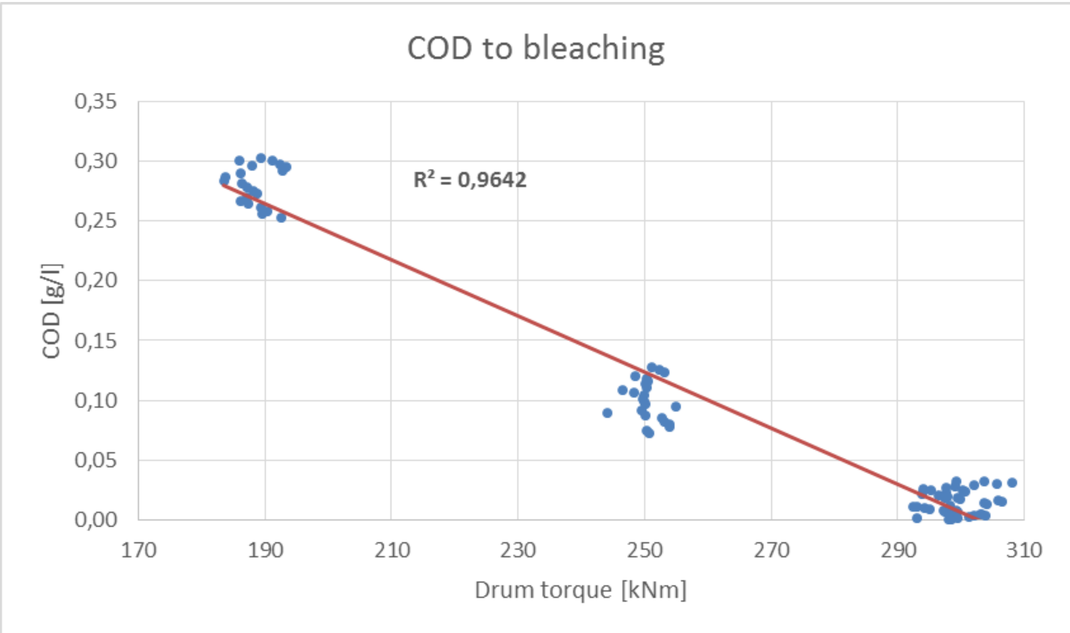


Figure 27 Effect of drum torque on oxygen stage washer cake discharge COD, measured with online refractometer.

Higher torque slows down the rotation of washer drum. Slower rotation increases the time for displacement to happen and thereby increases the displacement ratio. Figure 28 shows us the effect of torque to displacement ratio. During the trial run DR was at high level at high torque and started to collapse as torque was lowered. Displacement ratio would have gone a lot worse unless the test would not have been cancelled when the washing result started to deteriorate seriously. This was done to maintain the fiber line production at normal level.

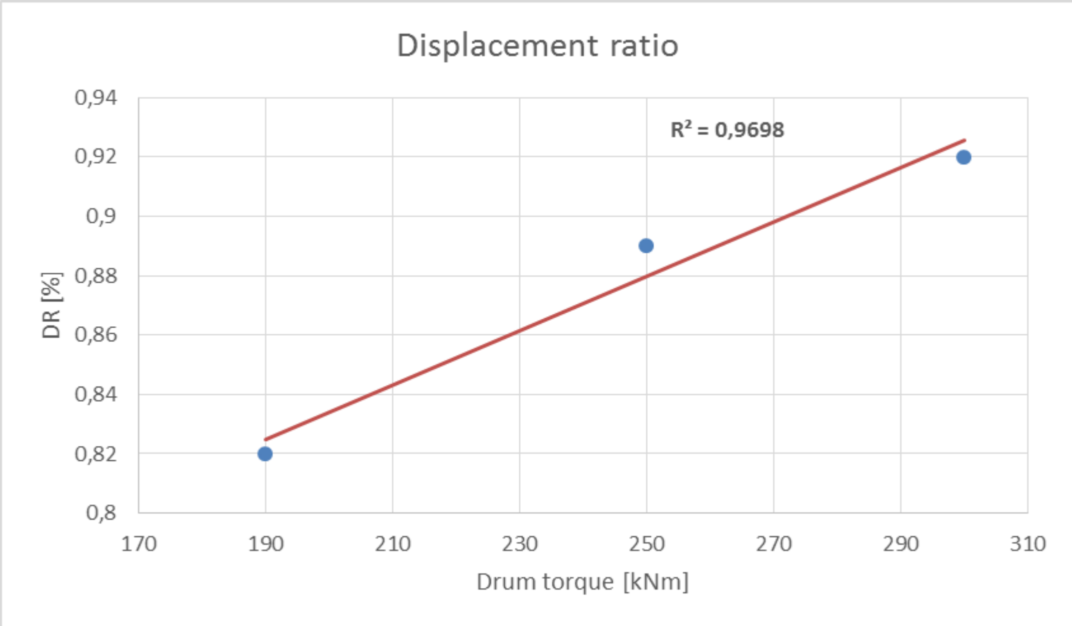


Figure 28 Effect of drum torque on displacement ratio. Displacement ratio is calculated from the dry solids of entering pulp, vacuum tank dry solids and wash water dry solids. Each presented displacement ratio point is calculated average of several data points.

On figure 29 are presented the conductivity and TDS of oxygen stage washer. Conductivity was measured from DD3 wash liquor circulation and TDS from the discharged pulp. Production rate was close to maximum during the whole trial. Results show, that increasing the washer drum torque the washing result is enhanced. When drum was operated at 190 kNm torque, the washing result was somewhat disastrous. TDS of the pulp was almost double compared to torque level of 250 kNm. Conductivity of the washers liquor circulation also contaminated as conductivity was more than double compared to torque level of 250 kNm. Further increase of torque did not affect the washing result so dramatically, but it was shown that best washing result was obtained when the drum was operated at 300 kNm.

Deterioration in washing result was evident as conductivity in washing water circulation at washer vacuum tank rose rapidly when lowering the drum torque. When torque was lowered below 200 kNm, concentration of easily washed inorganic substances exceeded the point where washing water contaminates accumulate to washing circulation and washing result deteriorates to inadequate level.

It would be best to operate DD3 washer at torque level of over 250 kNm, preferably close to 300 kNm. This correlates to theory as washer drum must rotate more quickly at low torque levels to maintain the same production rate. Cake thickness changed from 58 mm to 69 mm when torque was increased from 190 to 300 kNm.

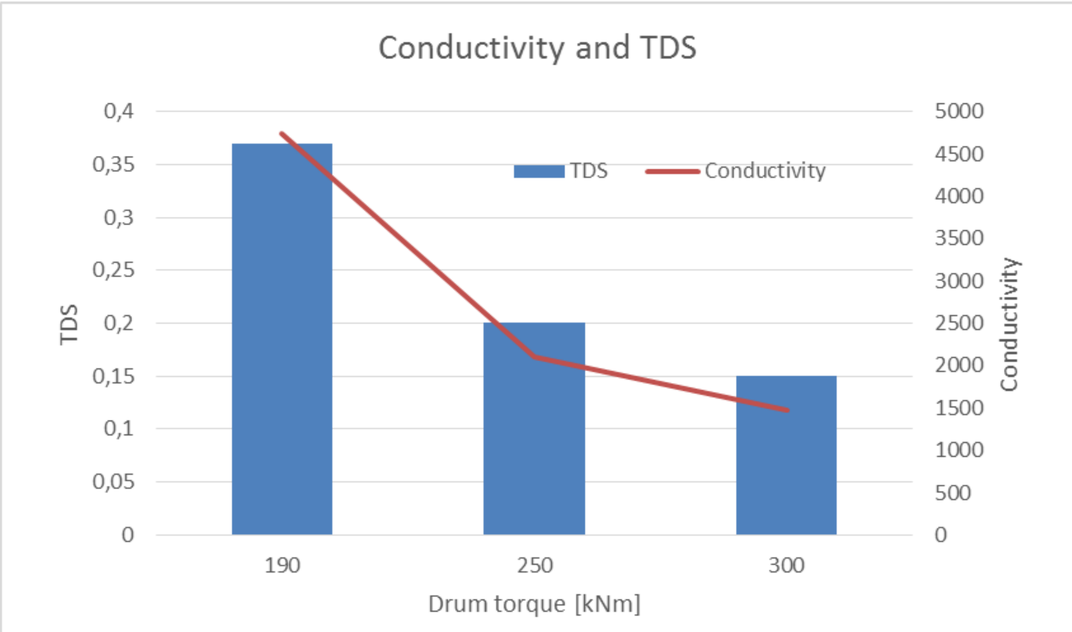


Figure 29 Effect of drum torque on TDS and conductivity. Both are measured by online devices from oxygen stage washer liquor circulation.

7.3 Washing temperature

Effect of washing temperature was evaluated by chancing the temperature of oxygen delignification washer wash water. Washing water originates from evaporation plant secondary condensate tank and it is heated with a steam operated heat exchanger from 60 °C to 90 °C. Typically washing water temperature is kept somewhere around 89 - 90 °C, depending on the operator.

During the trial run temperature was lowered to 85 °C and kept stable for several hours. After the temperature had leveled, changes to the temperature were made with 5 °C steps. Results of the trial were evaluated by monitoring the changes in the dry solids and COD leaving the washer and level of the dry solids and conductivity in the vacuum tank.

The results of the trial run were somewhat unreliable. It seemed that increasing the temperature from 85 °C to 95 °C could not statistically looking explain the effect of temperature. More likely changing pulp properties had bigger effect on the washing result, than temperature.

Figure 30 represents displacement ratio when temperature of the wash water wash increased from 85 to 95 °C. It is more than likely that properties of the pulp changed during the trial run, as according to literature lower temperature should result in worse washing result. Excluding the 85 °C from the observation, it can be seen that temperature rise has only a small, if any effect on the displacement ratio as 1 % change can be even a measurement error.

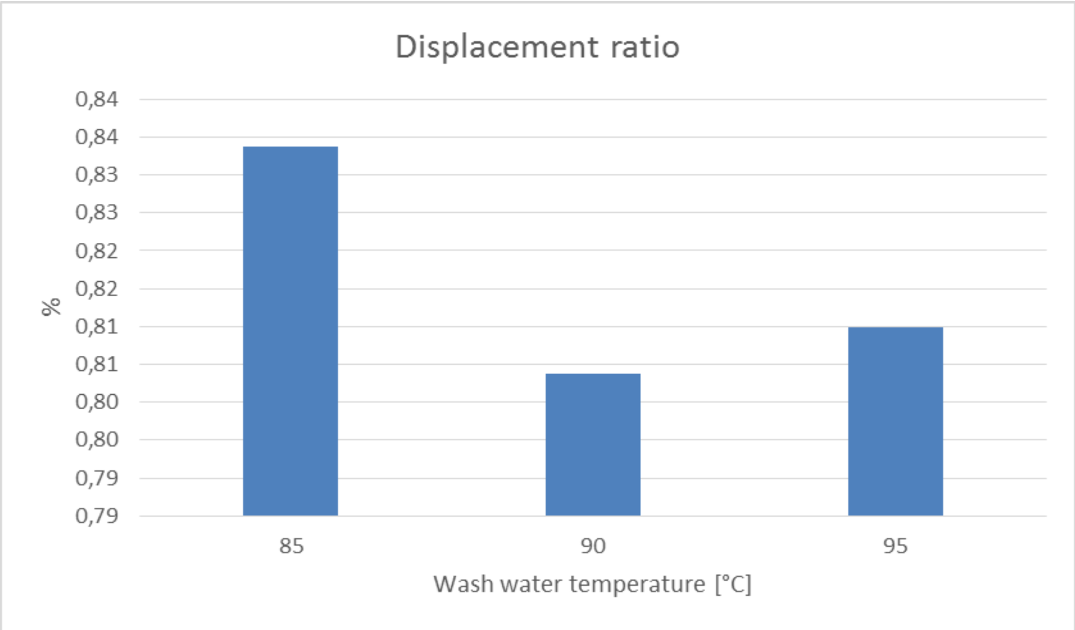


Figure 30 Effect of displacement ratio at different temperature levels. Displacement ratio is calculated from the dry solids of entering pulp, vacuum tank dry solids and wash water dry solids.

COD of the pulp (figure 31) during the trial run indicates the same kind of results as displacement ratio. At 85 °C level COD of the pulp is lower than expected. This can be explained as pulp property changes as displacement ratio was better at this temperature level. Considering only the two higher temperatures, can be noticed that increasing the wash water temperature to 95 °C lowers the COD by 35 %. Nevertheless it must be noted, that according to Kopra 2015 newest generation refractometer measurement accuracy at low concentration level liquids is ± 0,0015 % by weight, which means 0,15 mg/l resonance. Therefore the similar behavior between displacement ratio and COD can not be considered as reliable indicator of the temperature effect.

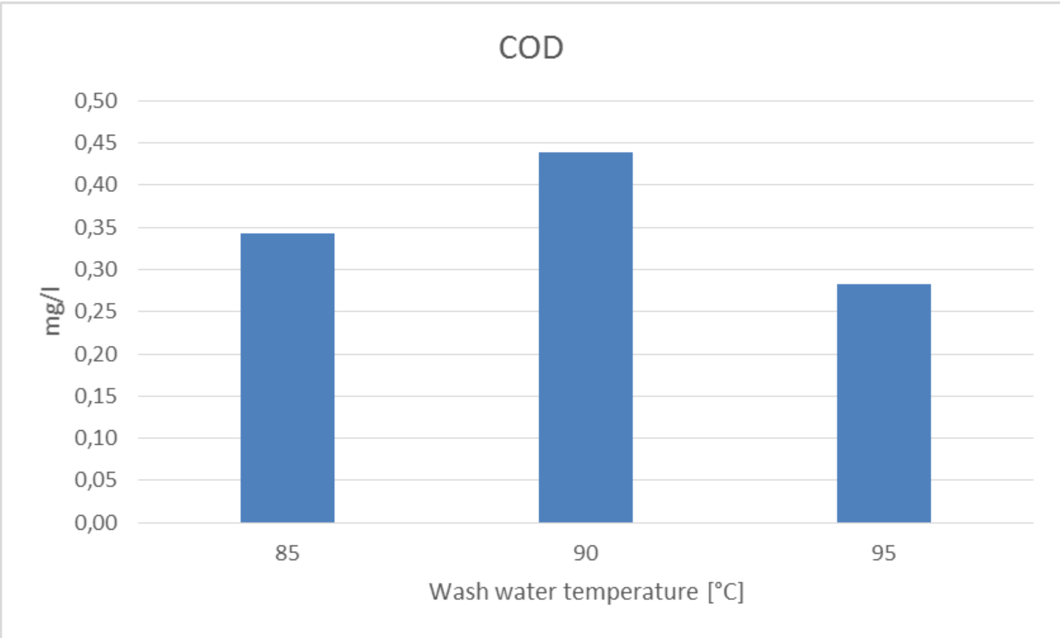


Figure 31 Temperature effect of pulp COD measured with online refractometer.

Total dry solids presented in figure 32 behaved according to displacement ratio and COD. Also TDS was the lowets at 85 °C and increase of temperature from 90 to 95 °C degreased TDS but the effect was so small it could not be verified to be caused by the washing temperature.

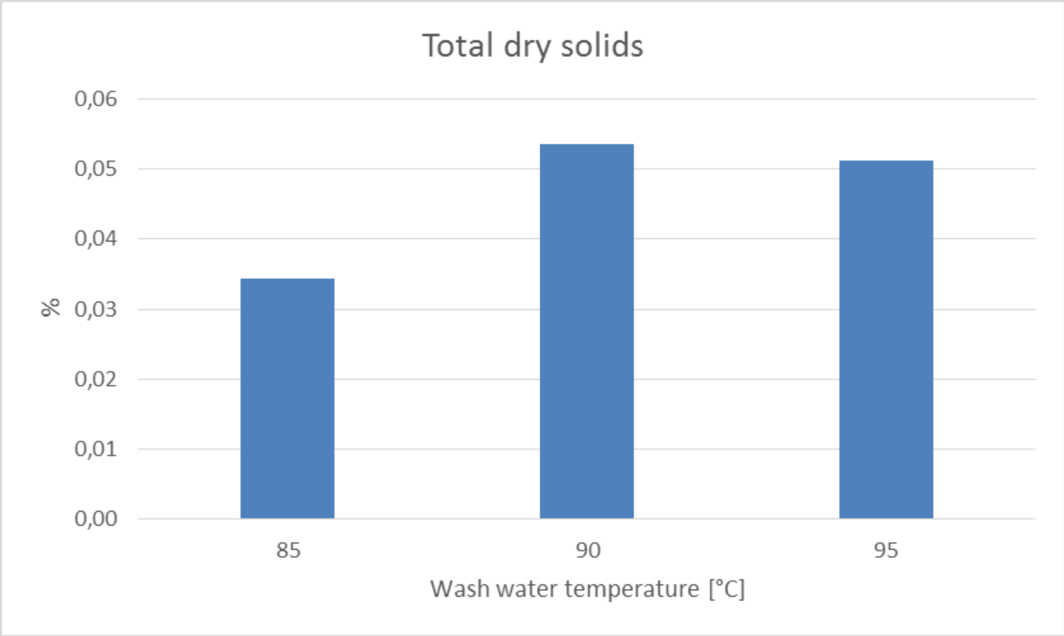


Figure 32 Total dry solids of the pulp to bleaching measured by online refractometer at different wash water temperature levels.

Biggest effect of wash water temperature has on the operation of hot acidic stage. As wash water temperature was lowered, the temperature of pulp exiting the washing stage was decreased as well. In order to maintain high temperature at hot acidic stage, it is essential to maintain wash water temperature at 90 °C.

Temperature can nevertheless be increased, as it improves hot acidic stage functionality and lowers the viscosity of liquor, enabling small enhancement to the washing.

7.4 Feed consistency

Purpose of the consistency trial was to determine the maximum consistency that could be fed to brown stock washers DD1 and DD2. It was supposed that the limiting factor in the trial would be the performance of the pre-thickener. As consistency rises, the flow resistance increases and causes the current of pre-thickener feed pump to rise to upper limit. There is a risk that consistency of the pulp gets too high and the pre-thickener gets jammed. In this case the pre-thickener probable has to be opened for cleaning.

If brown stock washers are driven without pre-thickener, excess liquor in pulp flow limits the production and lowers the washing result. The less liquor enters the washers, the less washing liquor is needed to displace it. This is one reason why feed consistency should be high.

Trial run was done by operating the line with upper level controls on for 8 hours with normal feed consistency. Then feed consistency was raised to maximum level that could be withstood consistently for at least few hours. Results of the trial were examined as total dry solids from the discharge of DD1 and DD2 as well as total wash loss variation at oxygen stage washer. All the samples were analyzed in laboratory, as there is only one measurement in entering and exiting pulp flow and washer performance cannot be evaluated individually with these.

Evaluated in kgCOD/ADt, washing loss increased in both DD1 and DD2 (figure 33) when consistency was increased. DD1 washing loss increased by 21 % and DD2 by 7 %. The reason for this was probably that bigger consistency forces the fibers more closely to each other and the penetration of the washing liquor is weakened. It seems that there is a certain point where extraction of the free liquor doesn’t enhance the washing performance any more.

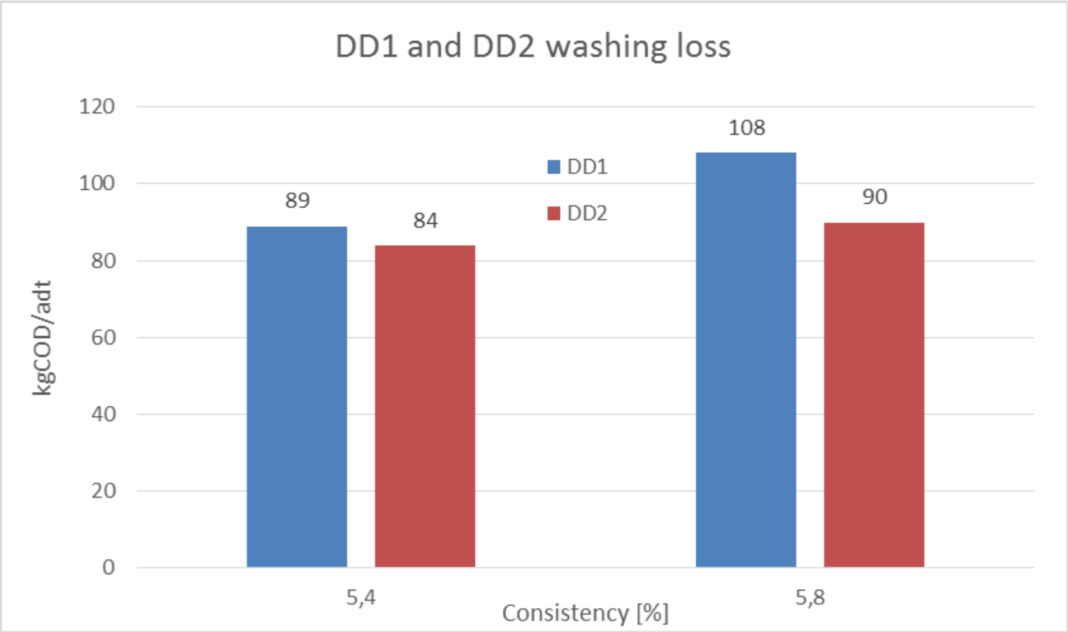


Figure 33 Brown stock washer washing loss in normal and maximum consistency. Samples were analyzed in laboratory.

Total dry solids content of the discharged pulp from DD1 and DD2 (figure 34) were at different levels while consistency was at normal operating level of 5,4. TDS was 12 % higher at DD1 compared to DD2 at the same production level. There are some fundamental differences between these two parallel installed washers and they cannot be compared directly.

Increase of consistency affected to DD1 TDS by increasing it only by 2 %, while DD2 was affected more and TDS rose by 10 %. The results are in line with previous operating experiences, as DD2 has always been more easily affected by process chances. When compared to figures 31 and 33 can be seen that COD load of DD2 does not increase as much as the conductivity of the pulp. This indicates that the deterioration in washing result particularly in the inorganic portion of liquor.

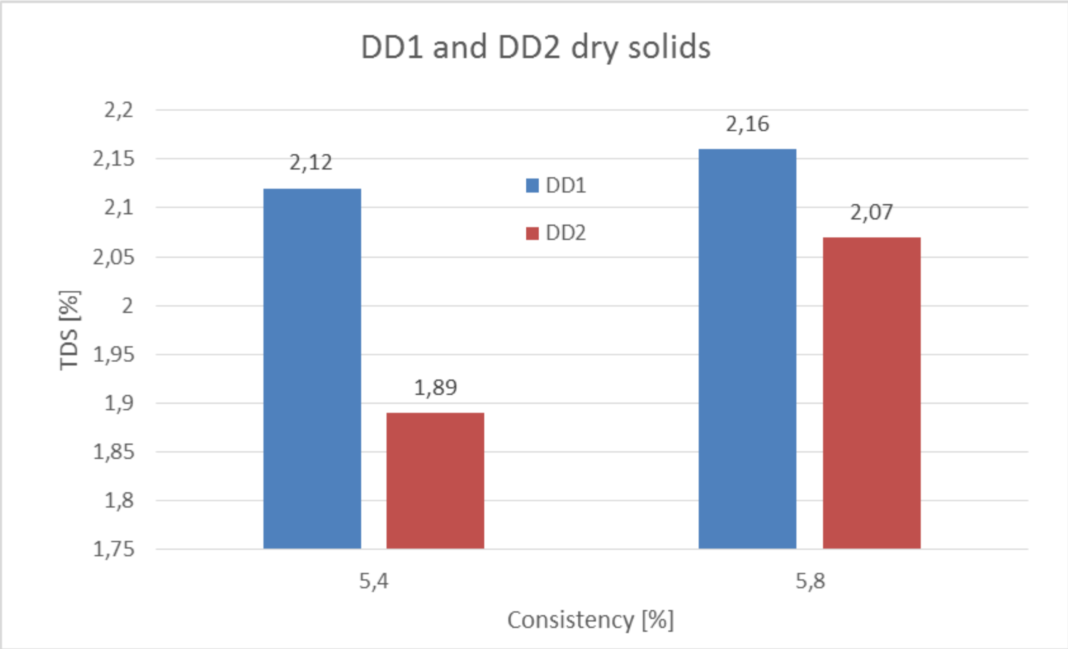


Figure 34 Effect of consistency change on total dissolved solid content measured from DD1 and DD2 cake discharge. Samples were analyzed in laboratory.

Results from the total dissolved solids analysis support the theory of exceeding the critical consistency, where flow resistance increase overcomes the benefit of drum rotation decrease. It can be notices, that DD2 performance decreases significantly when consistency is increased to maximum level.

Conductivity of the washers discharged pulp suspension expresses the performance when considering the removal of easily removed inorganic components from the pulp suspension. From figure 35 can be noticed that DD1 performance is somewhat unaffected by the consistency change, while DD2 pulp conductivity rises 10 %.

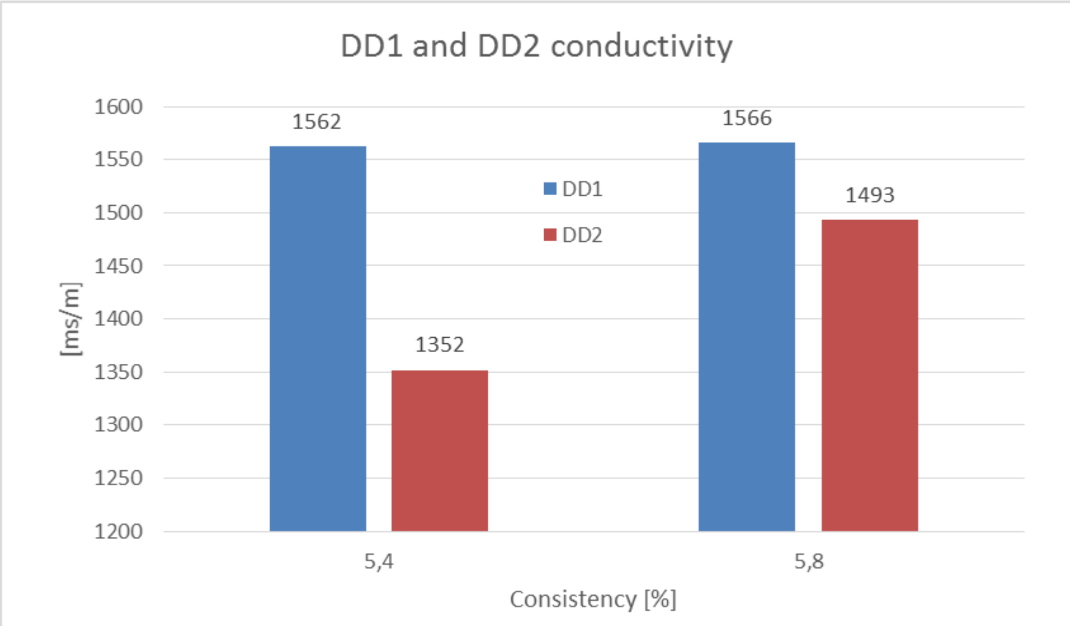


Figure 35 Conductivity of pulp discharged from DD1 and DD2 at different feed consistency levels. Samples were analyzed in laboratory.

From the result of the test can be noticed that changing consistency from 5,4 to 5,8 % decreases the removal of organic substances more at DD1 and inorganic at DD2 as drum torque was kept the same. Consistency increase lowers the washing result in both washers and unwanted organic substances are carried over to oxygen delignification.

7.5 Chlorine dioxide consumption

The effect of upper level controls to pulp cleanliness and thereby the consumption of chlorine dioxide was determined by running the washing stage with upper level controls on continuously for 2 weeks. Figure 36 presents the trial period nominal consumption per pulp ton. ClO2 consumption decreased 22,9 % (kgClO_2/ADt) from long time average (figure 34). At present chlorine dioxide production costs (Kauppinen 2015) and production level of 330 000 ADt/year this would lower the pulp bleaching costs by significantly. Also the deviation of chlorine dioxide usage dropped from 56 % implicating that the washing stage performance was more stable than before. This could also be seen from kappa deviation that reduced from 1,02 to 0,35.

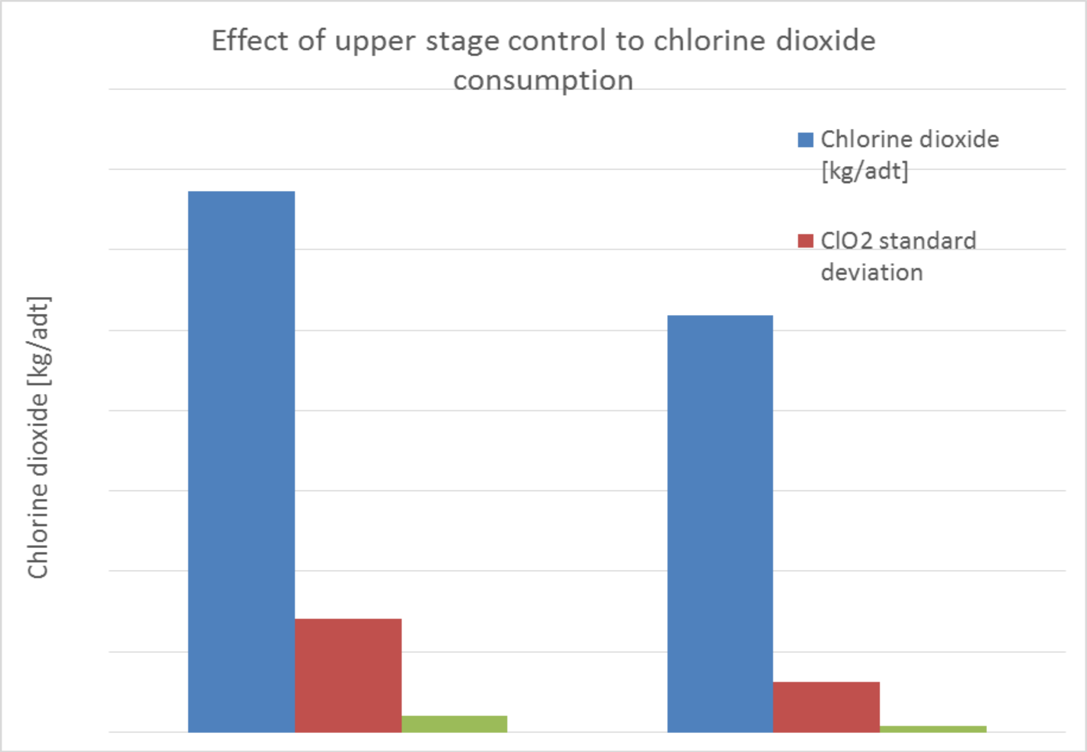


Figure 36 Effect of brown stock washing improvement on chlorine dioxide consumption, deviation and kappa deviation after brown stock washing. Evaluation was done by analyzing the information from the operations system.

7.6 Extractives removal

Washing efficiency of brown stock affects to extractives amount present in oxygen delignification and bleaching. Some of the extractive components are more easily washed away than others and for example betulinol is somewhat unaffected by oxidation and washing. Collection of different extractive components was evaluated from bleached pulp before the utilization of upper level control and during the trial runs. These are presented in figure 37.

From the results of extractive component analysis can be seen that total amount of extractives were at low level compared to previous results. The rise of extractive levels at the last quarter of the measurements could be related to fact, that washing stage was operated at low dilution factor level for a longer time. Easily washed components, such as fatty acids amount was lower than before after the utilization of upper level control, as well as the sterols. Betulinol amount was also at lower level but this could be explained by the differences between debarking at winter- and summertime. Nevertheless the same type of increasing behavior can be found in the betulin levels, when washing stage was operated at low dilution factor levels that varied between 2,7 and 3,0 m^3/ADt

Dilution factor was increased to 3,4 m^3/ADt at the end of the measurement period which can be seen as a drop in the extractive levels. This confirms the theory of extractive level dependence on the dilution factor.

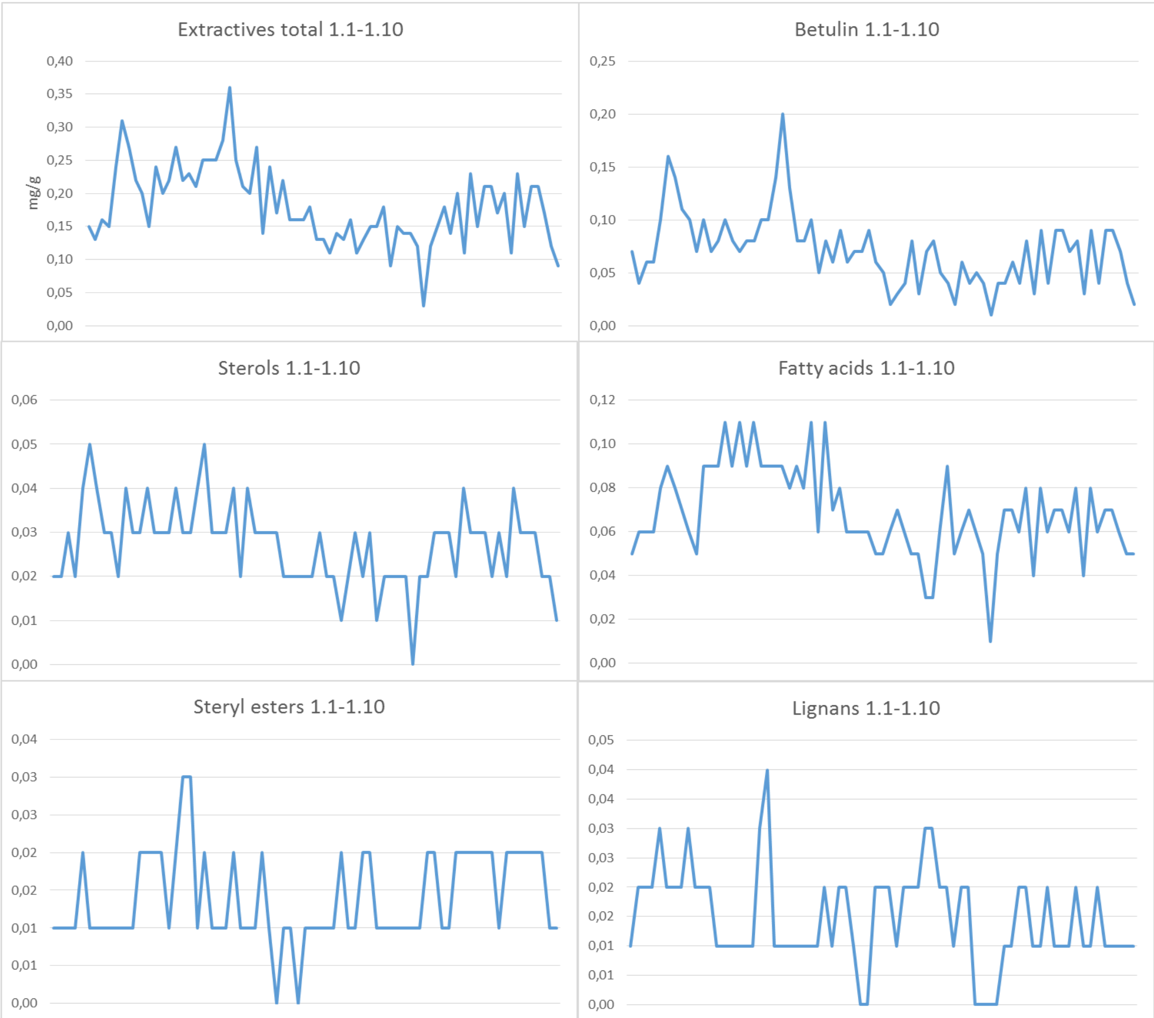


Figure 37 Analysis of extractive components found in bleached pulp before and after the utilization of upper level control. Upper level utilization was done in the middle of the observation period. Analyzes were made in UPM research laboratory. All presented as mg/g.

7.7 Performance of the equipment

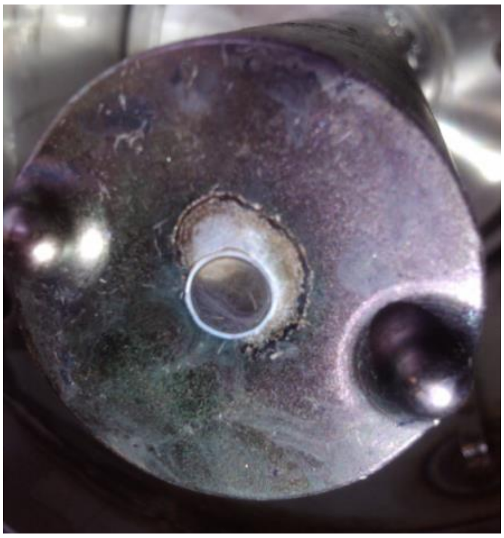
One major goal for this work was to bring the installed equipment to a more reliable operational state and to demonstrate that washing stage could be operated with upper level control continuously.

At the beginning many of the measurements were distorted by contaminants in the system and therefore unusable for controlling purposes. Refractometers installed in pulp suspension lines were operational, but liquor filtrate line measurements were in bad condition. Also upper level control needed updating as there were many data transfer and other problems.

At first the refractometers were cleaned and the functionality of the steam washes was made sure. After the maintenance, two refractometers installed in DD1 and DD2 filtrate lines started operating at proper level, but oxygen stage washer vacuum tank and washing liquor from oxygen stage washer to DD1 and DD2 measurements kept getting dirty as vacuum tank measurement lacked the steam washing and oxygen stage filtrate line steam washing was inaccurately installed and it did not clean the whole lens (picture 6).

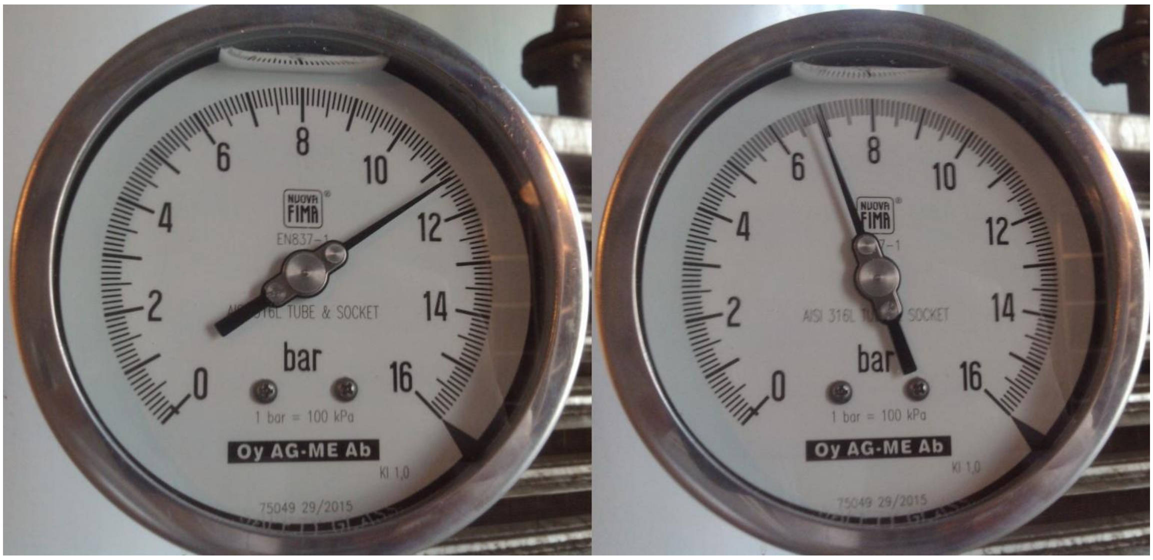
Steam wash was installed to DD3 vacuum tank measurement successfully and displacement ratio of oxygen stage washer could be considered as reliable tool. Oxygen stage wash filtrate refractometer was found out to be the most difficult to maintain proper operational state. Steam wash line dewatering valve kept jamming up letting the condensate accumulate to the steam pipeline resulting cold pipe full of water and no wash to the lens what so ever. Several attempts to fix the problem were made as it appeared that the dewatering valve was installed vertically and not horizontally as manufacturer prefers. Nevertheless, after proper cleaning of the valve it started to operate as expected.

The problem of misplaced steam wash nozzle made the measurement to drift away as contaminants accumulated part of the lens. Approximately 30 % of the lens was not affected by the steam wash. Correction to the nozzle was done at maintenance stop at hardwood fiberline in the end of the July.



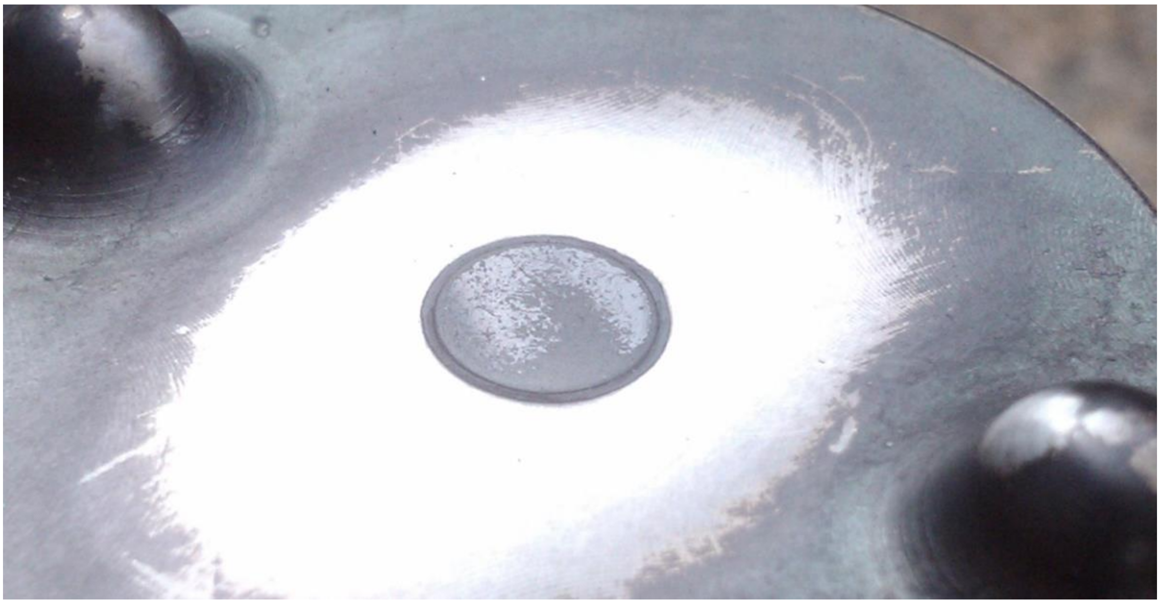
Picture 6 Misplaced steam flush at oxygen stage filtrate tank, 30 % of the lens was not flushed and measurement was faulty.

Oxygen stage filtrate measurement uses 10,5 bar steam for the refractometer lens cleaning. It was found that this might be too high for the cleaning purpose as there were evident wear in the lens at the beginning of the work and the same type of wear appeared to new lens that was replaced by K-patents. It is recommended that the pressure used for lens cleaning a low concentration areas 2 - 4 bar above the process pressure. Pressure at the filtrate pump pressure side is 4 bar, so 10,5 bar steam is 6,5 bars above the operating pressure and therefore far too high (Pictures 7 and 8). The pressure was lowered by installing pressure regulating valve with adjustment possibility to the steam line. Pressure was set to 7 bar, which is 3 bars over the process pressure.



Picture 7 Steam pressure at the DD3 filtrate tank was reduced to prevent damage to the measurement lens.

After the adjustment of the steam pressure the measurement device is supposed to remain in good condition. In the future if there is any similar damage in the lens, steam pressure could be decreased even more.



Picture 8 Damaged refractometer lens at oxygen stage filtrate tank outlet caused by too high steam pressure

Dilution factor for the washing stage cannot be defined precisely, unless the by-pass valve remains completely closed. From figure 38 can be seen the dilution factor in blue and by-pass valve in black. Straight brown line is the operator defined setpoint for dilution factor. It is evident, that as long as the by-pass valve is open, dilution factor will not be in the target zone as by-pass flow is not controlled. After the valve closes, dilution factor reaches the setpoint and levels to target zone. All the secondary condensate entering washing stage is now included in the calculations and dilution factor control and washing result is precise.

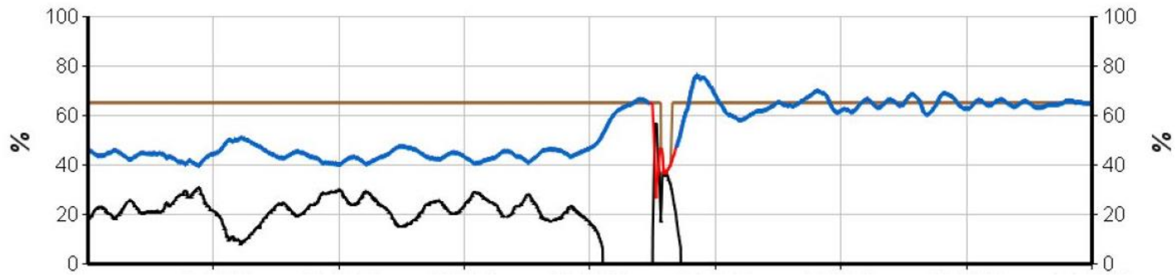


Figure 38 Filtrate tank of oxygen stage washer before and after closure of by-pass valve.

Another good example how upper level control defines the dilution factor is presented in figure 39. Blue line represents the timeframe when dilution factor control was on and immediately after it is switched off, dilution factor starts to wander off from the target. From the figure can also be seen how precise controlling of the dilution factor enables cost efficient usage of wash water.

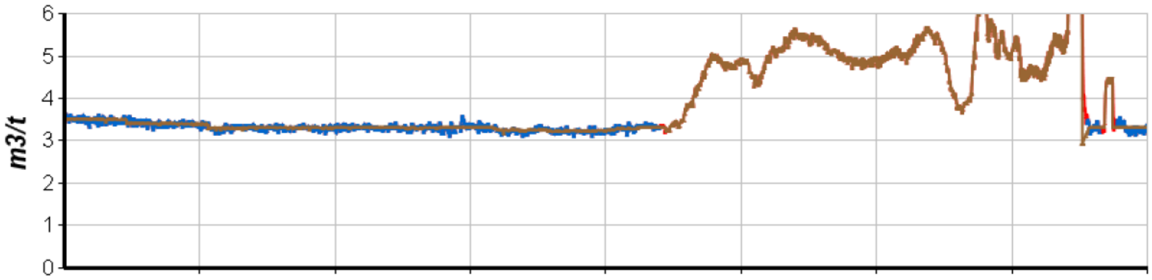


Figure 39 Effect of upper level control to dilution factor

Sulfuric acid (H_2SO_4) is added to pulp leaving the washing stage in order to lower its ph to 3,5. This is done to remove the hexenuronic acids in the storage tower 1, which operates as hot acidic stage.

However, addition of sulfuric acid strongly affects the measurement of total dry solids content of pulp exiting the oxygen stage washer. To demonstrate how sulfuric acid affects the measurement, the feed was completely turned off.

Figure 40 demonstrates how huge effect the addition has on measurement of TDS. Before sulfuric acid was turned off, measurement of TDS varied between 0,2 and 0,28 %. Immediately after feed of H_2SO_4 was turned off, measurement of TDS decreased rapidly close to 0. After the feed was returned, TDS rose also very fast to 0,14 % and started climbing slowly back to its original level.

This indicates that sulfuric acid is almost completely responsible for the formation of TDS in the pulp discharged from oxygen stage washer. It can be also stated, that washing of the pulp is done at excellent level and the pulp itself contains only small fraction of dissolved solids before the addition of H_2SO_4.

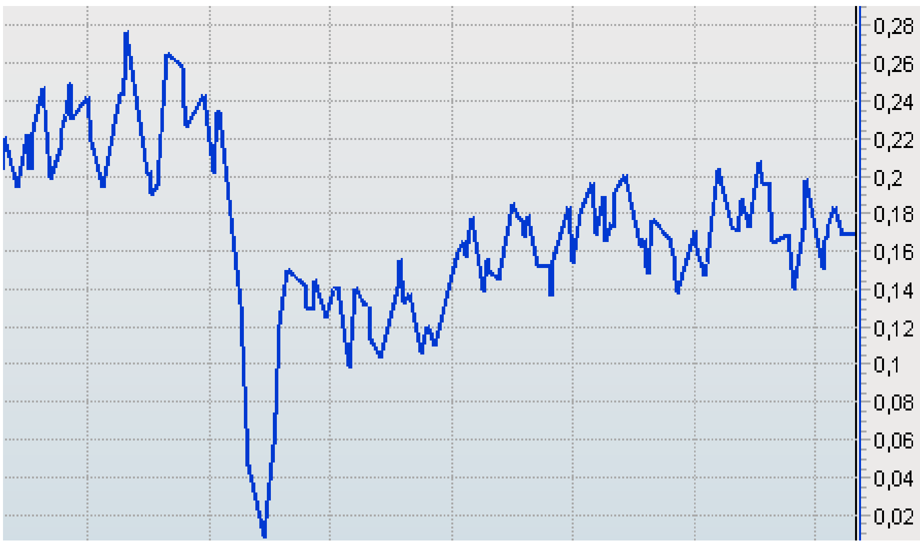


Figure 40 Sulfuric acid feed stopped to evaluate the effect to total dry solids. Measurement dropped from 0,22 % to 0,01 %.

8 CONCLUSIONS

In this study an upper level controlling system was utilized at Kaukas hardwood fiberline. Target for the work was to optimize the usability and functionality of the control to optimize the performance of brown stock washing. Improved washing resulted in decreased bleaching chemical consumption and more controllable evaporation plant load.

Priority number one was to bring the equipment and system to a state, where they could be used continuously. Also functionality of the control was improved to response more quickly to process changes.

Utilization of the upper level was successful and washing result increased significantly resulting in decrease of bleaching chemicals. Upper level control operation of the washing stage gained operators trust and eased up operational work. Upper level control also minimizes the operational differences between shifts as there are only few key parameters for the whole washing stage.

8.1 Control of brown stock washing stage

Stability and performance of the washing stage was improved as dilution factor and drum rotation controls proved to enhance the process remarkably. Washing stage dilution factor could be adjusted precisely and random fluctuation of dilution factor could be decreased. Rotational control with floating setpoint proved to be able to react with even sudden process changes and was found to be very useful after the correct operating parameters were found.

Upper level performance in terms of washing loss improved significantly. Organic and inorganic carry-over to bleach plant was reduced noticeably and the washing result was found to be a lot more stable.

Pulp filtration properties tended to vary from day to day, this was the case especially after production brakes. When pulp filtration properties were weak, it was found to be impossible to maintain DD3 filtrate tank level through oxygen stage washer. This caused by-pass valve to open and dilution factor to wander off from the setpoint and washing result to variate more. Therefore when all the washing water is not utilized at DD3 the performance of the washing stage cannot be judged with reasonable reliability.

When the mill was in normal operation at good production level, filtration properties of the pulp were better and upper level control operated as it should. It was most of the time possible to operate the washing stage continuously with the by-pass valve closed. Dilution factor was precise and washing result remained constant.

On the other hand, while by-pass valve remained closed for a longer time, the temperature of the DD1 and DD2 wash water was rather high. There is a heat exchanger installed before DD1 and DD2, but its capacity is far too low and is often bypassed due to its limiting nature in wash water flow. If wash water is too hot, there is a change it boils in the washer or in the inlet of the oxygen delignification feed pump. Boiling happens when the water enters a point where pressure is lower and this will deteriorate the washing result or damage the pump. There are plans of replacing the small heat exchanger with bigger one as this will solve the problem. After the upgrade there are no limitations to run all the washing water through oxygen stage washer and keep the by-pass valve closed.

8.2 Performance of upper level control

It was proven that utilizing upper level control, washing result could be improved and wash water amount reduced at the same time. Due to improvements at washing stage, bleaching chemical consumption was decreased to a level that caused problems with optimization of bleaching stage. The traditional upper level control of bleaching stage was found to be problematic and will probably be altered for better efficiency and more precise control of pulp end quality in the future.

Improvements made to online measurements enhanced the reliability of the refractometers. Problems at DD3 vacuum tank and filtrate tank outlet measurements were solved and could be trusted in a long run. Several smaller problems concerning measurements and the upper level control itself were fixed in order to make the system better and more easy to use. However, there is still a problem unsolved with the measurement of pulp leaving oxygen stage washer. Sulfuric acid added to the pulp after oxygen stage washer distorts the measurement and the problem could not be resolved during this work. The full potential of dry solids content measurement of pulp exiting the washing stage can be utilized when the dilemma of sulfuric acid addition can be solved. This also seemed to be a problem for the measurement device provider.

All the 7 other measurements proved to provide needed information about the chemical state of the process and upper level control could correctly respond by fine tuning the dilution factor accordingly. As dilution factor is set by operators and the refractometric measurements are only used to fine tuning, it is not disastrous if one or several measurements are at weak operational state. This would affect the tuning of dilution factor, but only slightly as dry solids is counted in as one of many correction factors. The correction factors were also fine tuned to quicker and more precise response.

Washing stage stability improved after the upper level functionality was utilized properly. Behavior of all 3 washers was found to improve as conductivity and TDS levels maintained a certain level for a longer period of time. Also oxygen stage functionality improved and kappa deviation to bleaching dropped significantly. Dry solid to evaporation plant increased and could be, due to precise dilution factor control, controlled more

All 3 washers could be run at high drum torque in normal operation, which enabled longer displacement time and better washing result. Floating setpoint enhanced the process so, that the control automatically altered the torque setpoint according to process conditions. In the time range of this work, there were no such process situations during normal operation that floating setpoint could not respond, not even at full production rate.

8.3 Cost effectiveness

More precise control of the dilution factor enables better utilization of wash water according to the process situation. This offers an opportunity to adjust the load of evaporation plant if needed. Evaporation costs at normal process situations could be changed by changing one single parameter, the dilution factor.

Bleaching costs decreased significantly after the utilization of upper level control. Improved washing enabled more precise utilization of bleaching chemicals which could be seen from the nominal consumption of chlorine dioxide per pulp ton. Total savings using the upper level control continuously with lowest possible dilution factor, taking account bleaching costs and evaporation of wash water, would rise up to millions. This can nevertheless be evaluated this easily, as process is at constant movement and optimal result requires fine tuning of the dilution factor according to the situation.

Utilizing all the wash water fed to washing stage at oxygen stage washer requires heating energy but it can be neglected as the costs are overwhelmed by savings from the bleaching chemicals and need of process steam at evaporation plant.

8.4 Recommendations for future

Operators need a lot more time to understand the operation of the upper level control at different process situations. After proper understanding of the meaning and effect of different parameters, a stable and cost effective operating of the washing stage can be achieved.

Heat exchanger of DD1 and DD2 wash liquor should be upgraded for better adjustment of wash water temperature. This will resolve the possibility of flashing in the washers and enable higher wash water temperature at oxygen stage washer.

There are problems concerning oxygen stage feed pump. At high production and consistency levels the pump will not operate properly at certain process situations. Upgrading the feed pump to a bigger one would enable increasing the consistency and thereby enhance the operation of oxygen stage washer as flow rates would be decreased.

Performance of the washing stage could be evaluated regularly by measuring the TDS and COD wash loss from oxygen stage washer cake discharge, as this is the point where washing loss is finally determined. Same type of manual sample taking device could be installed to hardwood fiberline as there is on softwood fiberline. This would ease up sample taking and problem solving in challenging process conditions.

Although refractometers are used only to fine tune the process, it would be wise to maintain them in good working order. Regular checks should be made to assure all the measurements are working as they should. This would promote the performance of the washing stage and enable best possible operation.

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