Energy efficient control techniques in continuous cooking application

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Abstract: Energy efficiency is one of the main aspects in the Kraft pulping process. In Kraft pulping, the delignification of the pulp is mainly controlled by temperature and alkali. However, the quality is usually measured only in the blowline of the digester resulting in a control delay several hours. This affects to the quality control and also the energy efficiency of the plant. In this study, energy efficiency in the continuous Downflow Lo-Solids® cooking application is studied using model-based approach. Temperature and alkali controls are considered and some suggestions are proposed.

Keywords: Temperature control, chemical variables control, pulp industry

1. INTRODUCTION

Continuous cooking application is one of the main sub processes in fiber line. In continuous cooking process, the major part of the delignification takes place in the digester. Thus, it is challenging to control the variation in the Kappa number at later stages after the cooking process. The continuous digester is complicated system with long residence times as well as difficult and often insufficient measurement points. High pulp capacity demands and highly alkaline conditions prevent the measuring of temperatures and alkali content inside the digester. Thus, the measurements are located at the input and output flows and on the outside wall of the digester. This causes challenges to the digester control.

The production rates in continuous cooking processes have increased continuously. This is challenging in undersized equipments. That set demands for process control and can cause faults and disturbances which affects the quality of the pulp. If the disturbances move too far along the cooking it is possible that the production must be reduced which in turn causes economical losses to the mill. In order to normalize process operation properly after a process fault the identification of faults should be done as soon as possible.

The front-end of the Kraft pulping process has a great influence to the controllability of the process (i.e controllability of steaming vessel in vinter time). the quality of the pulp. The main reasons are the changing raw material (chip quality), see e.q. Gullichsen et al. [1992], inaccurate measurement of the wood charge (production rate measurement) to the cooking, inefficient air removal and the control of the impregnation. The effect of front-end processes has been studied for the softwood in the research of Malkov [2002]. For example, screw can be unevenly filled during the operation. Since the rotation speed is used in the liquor to wood and alkali to wood ratio controls, variations to these controls may result.

There are many disturbances in the digester control. The main uncertainties and difficulties in the digester control are the following (Lundqvist [1990]):

(1) the varying and unknown properties of the chips entering the digester system,
(2) the behavior of the chip column, the many complex phenomena involved in impregnation, cooking and washing and
(3) the long time delays and the lack of good sensors for crucial variables.

Due to these aspects, it is very difficult to observe chemical reactions and material flows in the digester (Lundqvist [1990]). One of the major disturbances in continuous cooking is the varying chip size, which could cause problems in the digester (Tikka et al. [1988]), such as unwanted cooking properties. Another major disturbance is the abnormal compaction. Compaction has been researched and simulated for example by Miyanishi and Shimada [2001], Saltin [1992] and Härkönen [1987]. One faulty situation affecting the pulp quality is the channelling of the washing liquor in the washing zone. This can also cause variance to the blow-line pulp consistency and process delays.

The main idea in this study is to consider the control of the alkali and temperature in continuous cooking application. The control of the alkali is not only affecting the chemical consumption, but also the savings in the energy can be significant. Pulp yield is also affected by alkali control and the production of the pulp is higher while using less raw materials (wood chips, chemicals, etc.).

In pulp mills, the alkali is controlled by dosage control and alkali profile control. Thus, alkali to wood ratio (alkali divided by moisture free wood) is kept constant depending on the species produced. The variations in white liquor conceentraton and chip quality must be taken into account in control strategy. In many mills, the alkali is dosed into several points. This is called alkali-profile control strategy. This is especially applied for the modified cookings, such as Lo-Solids®. The residual alkali in the ciculations and extractions can be measured i.e using on-line alkali measurements. This measurement can be applied for the control of the residual alkali. The liquor to wood ratio is controlled by black liquor addition.

The structure of the paper is as follows. The process is introduced in section 2. In section 3, methods and proposed control strategies are revised. Results and discussion are shown in sections 4 and 5 and conclusions are presented in section 6.

2. CONTINUOUS COOKING PROCESS

The studied process is a Downflow Lo-Solids® (Marcoccia [1996]) cooking process (Fig. 1). The chips are impregnated in the impregnation vessel (I1-I2) and in the first zone (D1) of the digester. Between upper extraction and cooking circulation there is a counter-current zone (D2). In this zone, black liquor is displaced with cooking circulation liquor which temperature and alkali concentration are high. One of the purposes of the cooking circulation is the uniforming of the temperature and alkali concentrations. The lignin is mainly removed in the comparatively long co-current cooking zone (D3). There is a short washing zone at the bottom of the digester. Softwood chips mainly consist of pine chips and hardwood chips consist mainly of birch chips.

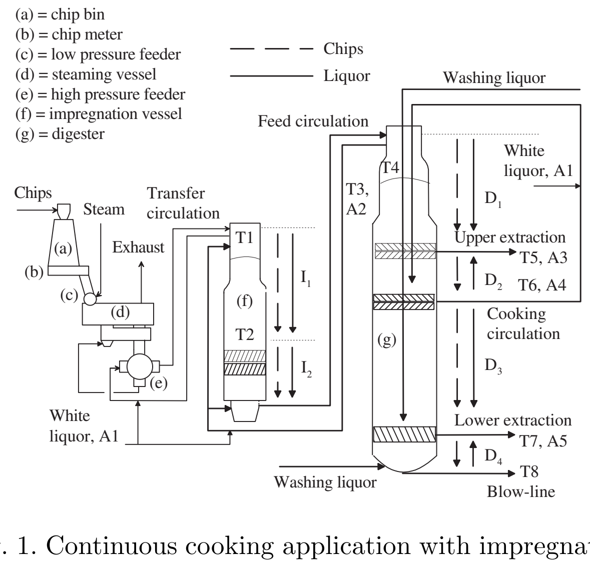

Fig. 1. Continuous cooking application with impregnation vessel and digester.

In the initial phase, about 60 % of the alkali charge is consumed and the amount of carbohydrates decreases rapidly in the softwood pulping, see Figure 2. The delignification rate is small compared to carbohydrates dissolution in the initial phase. In the bulk phase, the delignification rate is fast and the carbohydrates dissolution and alkali consuming is small. Olm and Tistad [1979]

The effective alkali concentrations of the white liquor (A1), digester feed circulation liquor (A2), two black liquor ex-

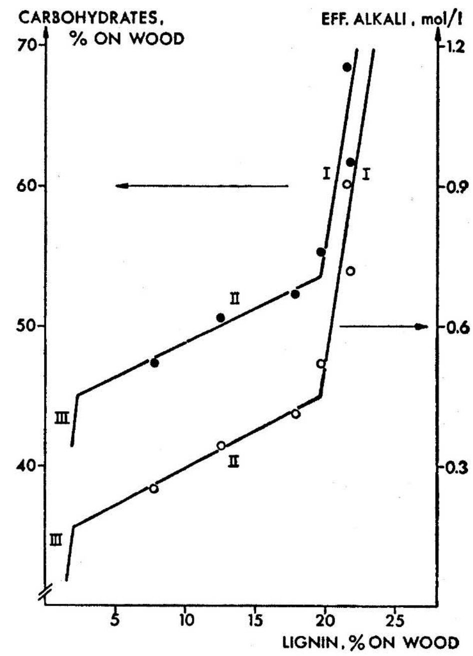

Fig. 2. Carbohydrate yield (% on dry wood) and effective alkali concentration in cooking liquor as a function of lignin content (% on dry wood). Olm and Tistad [1979]

tractions (A3 and A5) and cooking circulation (A4) are measured. The white liquor is added to the impregnation vessel's transfer circulation, to the digester's feed circulation and to the cooking circulation. Temperatures (T1-T8) are measured from the liquor circulations and from the heating steam at the top of the digester.

3. PROCESS MODELS

3.1 Delignification and carbohydrate dissolution

The model development has been based on the studies of several researchers (see, e.g. Gustafson et al. [1983], Pu [1991], Agarwal and Gustafson [1997], Rantanen [2006] and Ahvenlampi et al. [2010]). The delignification model structure and the species specific parameters in different zones are presented in paper Ahvenlampi et al. [2010]. Gustafson et al. [1983] have derived a mathematical model consisting of a series of differential equations describing the combined diffusion and kinetics within a wood chip during the kraft pulping process. Gustafson *et al.* developed and verified the model originally for softwoods.

The equation of cellulose dissolution in the initial phase (I1 and I2 in Fig. 1) are given by:

$$\frac{\partial C}{\partial t} = -e^{(Ai1-Bi1/T)}[OH^-]^{Oi1}(C-Cr)^{Ci1}, \qquad (1)$$

$$\frac{\partial H}{\partial t} = -e^{(Ai2-Bi2/T)}[OH^-]^{Oi2}(H-Hr)^{Hi1}, \qquad (2)$$

where C and H are cellulose and hemicellulose contents (% on wood), C_r and H_r are unreactive cellulose and hemicellulose contents (% on wood) and $[OH^-]$ is the hydroxyl ion concentration.

Cellulose and hemicellulose dissolution in the bulk phase (D1-D4 in Fig. 1) is:

$$\frac{\partial C}{\partial t} = -e^{(Ab1-Bb1/T)}[OH^-](C-Cr), \quad (3)$$

$$\frac{\partial H}{\partial t} = -e^{(Ab2-Bb2/T)}[OH^-](H-Hr), \quad (4)$$

3.2 Alkali consumption

Alkali is one of the main control variables affecting to pulp quality. Cooking alkali is controlled by alkali to wood ratio and the alkali (white liquor) is added to several places in the cooking application, see Figure 1. In the studied application, alkali addition is made to three flows (the transfer circulation flow of the impregnation vessel, feed circulation flow of the digester and cooking circulation in the digester). The alkali is impregnated into the chips in the impregnation vessel, before the cooking operation in the digester. Air is removed from the chips before impregnation vessel, so that the impregnation of alkali into the chips becomes easier.

In the initial phase delignification, about 60 % of the alkali is consumed and carbohydrates degrade rapidly (Olm and Tistad [1979]). According to Rekunen et al. [1980], about 50 % of the effective alkali is consumed during initial phase with softwood. In the study by (Chiang et al. [1988]), it was shown that the hardwoods consume more effective alkali prior to the initial phase than softwoods. However the total consumption after initial phase was about the same for the hardwoods and softwoods. About 20-25 % of the hardwood lignin was dissolved during initial phase compared to the 13.5-17 % during softwood pulping. Also the bulk delignification was about 1.2-1.8 times faster for the hardwoods.

In this study, alkali models are based on the equations presented by Pu et al. [1991] and Vanchinathan and Krishnagopalan [1997]. In the article Vanchinathan and Krishnagopalan [1997], equation 5 is presented for initial phase

$$\frac{\partial OH}{\partial t} = b_{i,OH} L \quad (5)$$

For bulk phase, equation 6 is suggested in papers (Pu et al. [1991] and Vanchinathan and Krishnagopalan [1997])

$$\frac{\partial EA}{\partial t} = [b_{1,OH}\frac{\partial L}{\partial t} + b_{2,OH}(\frac{\partial C}{\partial t} + \frac{\partial H}{\partial t})]/(0.1 * LW), \quad (6)$$

where b are coeffients, L is lignin, C is cellulose, H is hemi cellulose and LW is liquor to wood ratio.

4. PROPOSED CONTROL TECHNIQUES

4.1 Temperature control

In industrial plants, the Kappa number control is usually performed by the H-factor Vroom [1957]. The H-factor expresses the cooking temperature and time as a single variable. Based on the difference between the predicted Kappa number and the Kappa number target the H-factor and temperature profile are corrected. One weakness of the H-factor is that depending on the variations in chip quality etc. different H-factors are needed, although the process conditions were otherwise the same.

In paper Ahvenlampi et al. [2009], is proposed that the temperature in impregnation vessel should be controlled and stabilized. However, this kind of temperature control was not possible to take into account in the studied plant.

Operation in the washing zone in the digester is dependent on the production rate and washing ratio. In this study, temperature control is proposed for the washing liquor flow control. The idea is to keep the blow line temperature constant to enhance washing efficiency in the digester and also help the following washing processes. The control is applied in cascade mode from blow line temperature to the temperature control for incoming washing liquor to the cooking application. Heat exchanger is used in the temperature control. In the studied plant, conventional and Downflow Lo-Solids® cooking application processes are used. The proposed control technic was tested in the short washing zone in Downflow Lo-Solids® cooking application.

4.2 Alkali control

In chemical pulping plant, the alkali dosage and alkali splits are not typically controlled by model-based controls. When using models the savings in the raw materials and energy can be significant. Pulp yield can be also optimized.

Studies have shown that the strength of white liquor, the principal cooking chemical, may vary by about 5 % or even more after production breaks. The alkali to wood ratio control must compensate for this variation, otherwise it will have significant effects on cooking conditions and pulp quality. Some mills control the alkali to wood ratio according to laboratory measurements of white liquor. This is a very inaccurate control strategy. By using online analysers more accurate control is achieved. The sampling period is about 15 minutes in on-line analysers, depending on how many sampling points are used. If needed, the analyzer could also be put to measure only one sample point, giving a new result every 5 minutes.

Residual alkali concentration cannot be too low or the pulp quality and bleachability can be decreased. If alkali concentration at some stage of cook drops too low, lignin begins to precipitate and the pulp will be very hard to bleach. This will in turn result in yield and strength losses and high chemical consumption in the subsequent oxygen delignification and bleaching stages. But high residual alkali concentration is harmful as well, particularly in the beginning of cook: it increases cellulose degradation, i.e. reduces pulp yield, and increases chemical consumption. Reliable alkali measurements and models are therefore needed especially in modern cooking processes that aim to lower the initial alkali levels and to maintain a more stable alkali profile throughout the cook.

The model based alkali content control strategy is proposed for the continuous cooking application. The alkali content prior to the impregnation is modelled and the control is applied according to the alkali concentration. Thus, different operation conditions can be controlled more efficiently compared to the prosentually controlled alkali splits. The alkali to wood ratio is kept constant.

Also the yield of the process can be evaluated using the proposed control strategy.

In this paper, the chip moisture content measurement is proposed to take into account in the alkali and liquor to wood ratio controls. The results of the effect of the moisture content change to the the alkali and liquor to wood ratios in the studied mill are presented.

5. RESULTS

Figures 3 and 4 present the proportionable alkali to wood ratio and liquor to wood ratio as the moisture content is changed from 45 % to 55 %, respectively. Plant data is used and only the moisture content is changed in calculations.

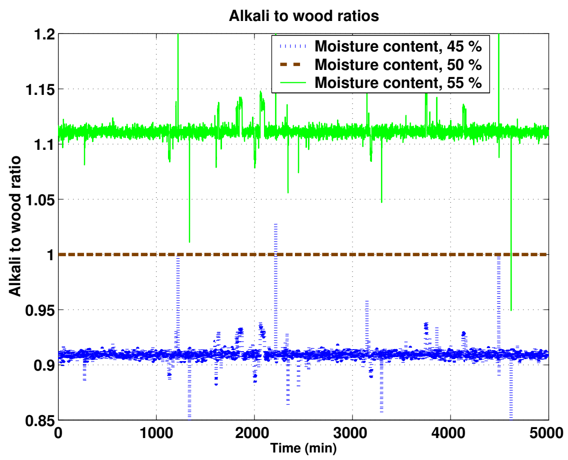

Fig. 3. Alkali to wood ratio, if the moisture content is changed from 45% to 55%.

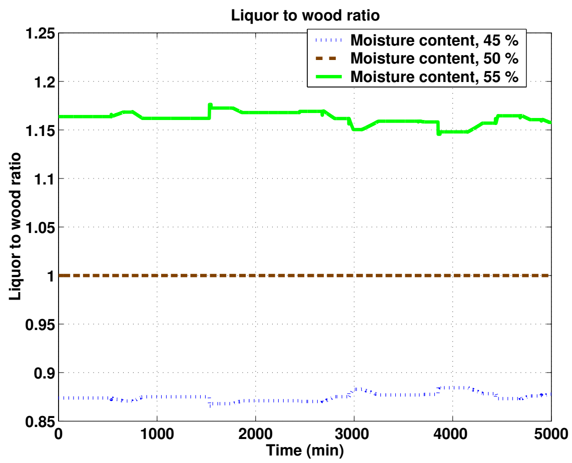

Fig. 4. Liquor to wood ratio, if the moisture content is changed from 45% to 55%.

Figure 5 shows the modelled alkali concentration before the impregnation vessel and modelled and measured alkali concentrations in the feed circulation of the digester.

The blow line temperature measurement before and after control change are shown in Figures 6 and 7, respectively. As can be seen there is variation in the temperature, before the control change.

Figures 8 and 9 present the hemicellulose and cellulose dissolutions in impregnation with different alkali contents.

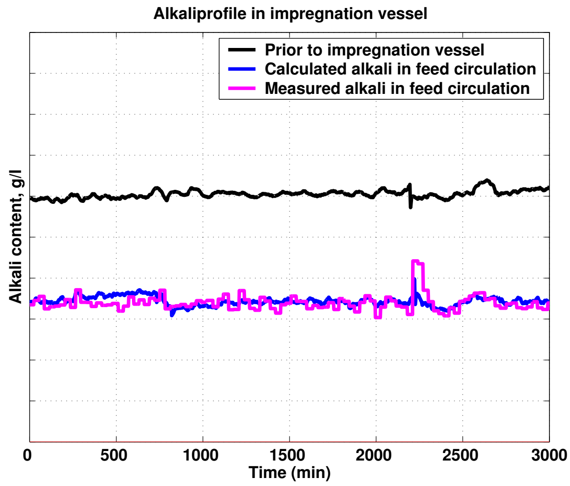

Fig. 5. Alkali concetration in impregnation vessel.

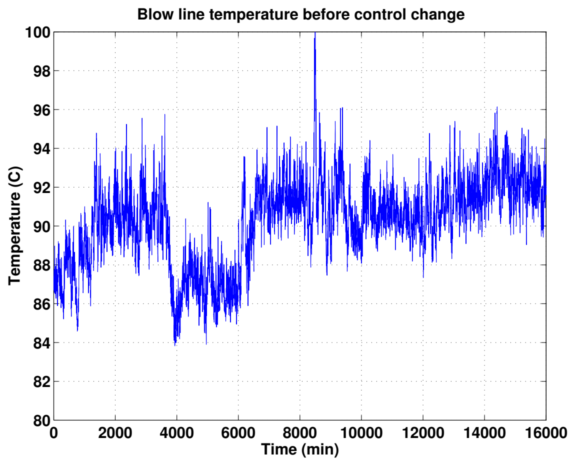

Fig. 6. Blow line temperature, before control change.

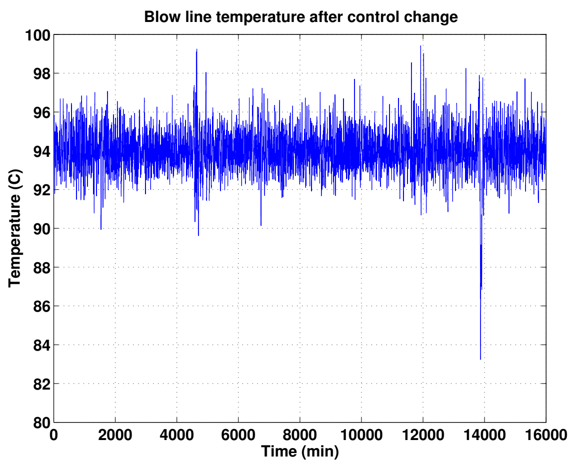

Fig. 7. Blow line temperature after control change.

The x-axis is scaled that the 100 means 50 % moisture content and 90 % is about 45 % and 110 % is about 55 %. As can be seen the moisture content has big effect especially to the hemicellulose dissolution in impregnation vessel.

Figures 10 and 11 illustrate the hemicellulose and cellulose dissolutions in impregnation with different temperatures

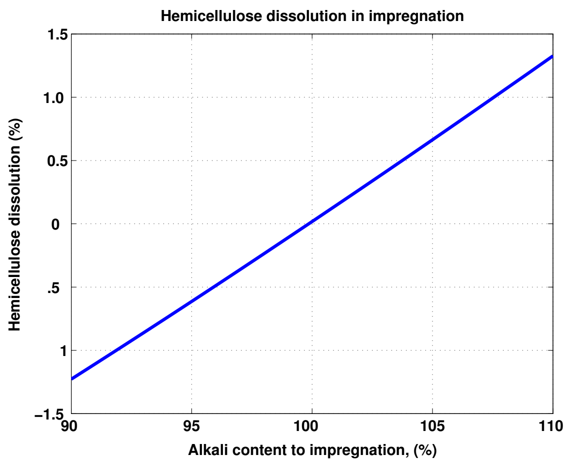

Fig. 8. Hemicellulose dissolution in impregnation in different alkali dosages.

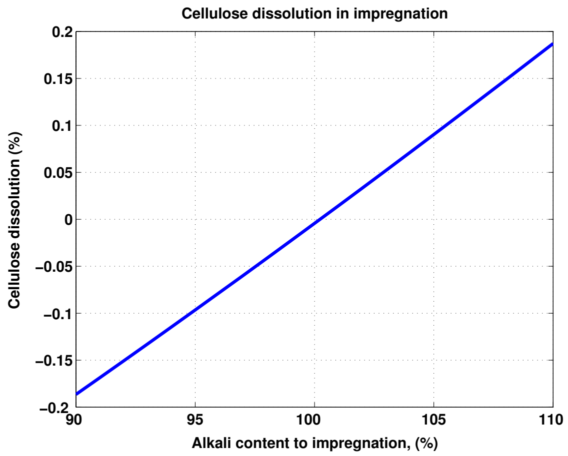

Fig. 9. Cellulose dissolution in impregnation in different alkali dosages.

in impregnation vessel. The x-axis is scaled so that the 0 means normal temperature in impregnation vessel and -10 and 10 are as deviations from the normal opereration.

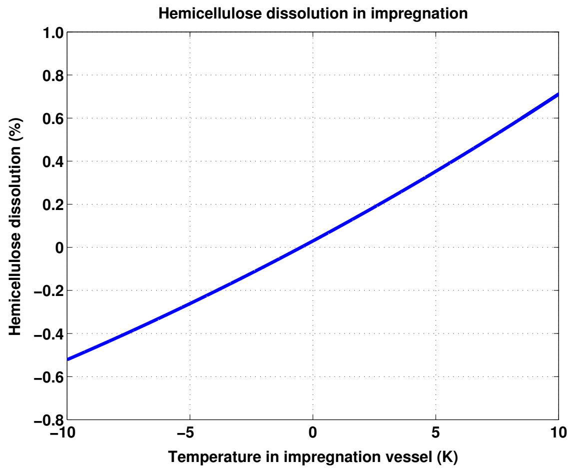

Fig. 10. Hemicellulose dissolution in impregnation in different temperatures.

Figure 12 shows the modelled Kappa number (upper plot) and alkali content in cooking circulation (lower plot).

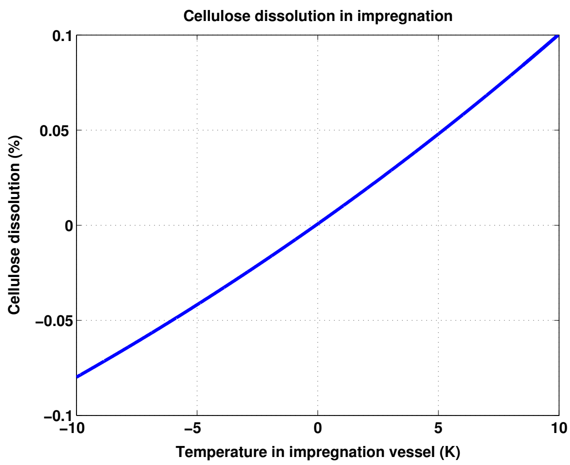

Fig. 11. Cellulose dissolution in impregnation in different temperatures.

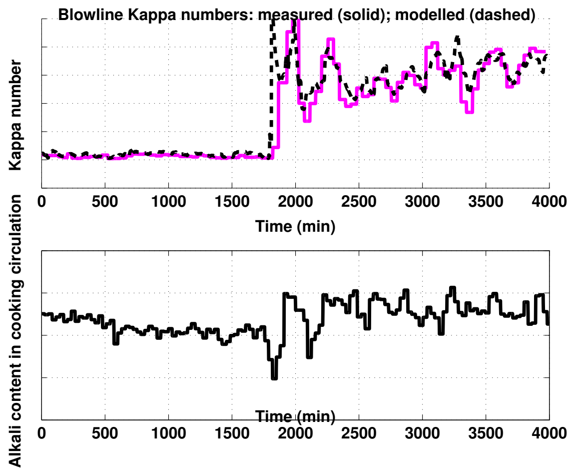

Fig. 12. Blow line Kappa number vs alkali content in cooking circulation.

6. DISCUSSION

Raw material, chip dimensions and air removal efficiency vary prior to impregnation. The objective of impregnation is to distribute cooking liquor uniformly into the chips. If the air removal is not sufficient or chips are not screened properly the impregnation result is poor. Also temperature, alkali and residence time (production rate) affect to the goodness of impregnation. The importance of the impregnation prior to cooking is widely recognised in the pulping industry. Poor impregnation results in higher rejects and higher lignin content at a given yield. Complete impregnation increases pulp uniformity.

In an earlier study, the delignification model parameters for studied process were presented (see, Ahvenlampi et al. [2010]). In Ahvenlampi et al. [2009], the models where used to study the effect of the impregnation vessel to the quality variation in blow line of the digester. The temperature changes in impregnation vessel had great effects to the quality (Kappa number and yield).

The effect of the chip moisture content to the alkali and liquor to wood ratio controls in the studied mill are presented in Figures 3 and 4. In this study, the chip moisture change is tested in the range 45 - 55 %. The change in the alkali and liquor to wood ratios is even over 10 %, if the moisture content is changed 5 %. This will affect to the quality of the cooking (Kappa number) by some Kappa numbers. However, the moisture content can variate even more in pulping mills. Thus, the effect will be more dramatic to the operation and quality of the cooking process. The use of the reliable chip moisture content measurement in these controls would enhance the raw material efficiency and quality of the cooking.

As can be seen from the Figures 8-11, the alkali concentration has bigger effect to the hemicellulose dissolution in impregnation vessel than temperature in the normal operation range in the studied mill. The mass-balance based alkali content model for transfer circulation is implemented to the automation system. In this study, the model based alkali control is proposed for continuous Downflow Lo-Solids® cooking application. By controlling the alkali concentration (not alkali dosage percent) before the impregnation vessel, it is more effective to control especially the hemicellulose losses in continuous cooking applications. From the Figure 12 can be seen that the alkali change in cooking circulation has great effect to the blow line Kappa number.

The blow line temperature varies in many pulp mills. It is energy efficient to control the blow line temperature to get more even washing in digester and the washing in following washing processes is esier. The proposed control technique has been tested in the studied mill since November 2009 and results are promizing, see Figures 6 and 7. The blow line temperature control has been in use after the implementation. The variation in the blow line temperature has been reduced and it has been also possible to increase the blow line temperature using the strategy.

The pulp yield (decrease or increase) affects also to the material flow (lignin etc.) into the recovery boiler. Thus, less or more energy can be produced from the wood raw material in recovery boiler. If the cooking models and controls are reliable, the material flow from the cooking application could be optimised into fiber line or recovery boiler depending on the income from the fiber line product and energy produced in recovery boiler.

7. CONCLUSION

In this study, energy efficient control techniques are presented for the continuous cooking application. By using the techniques, raw material efficiency and the yield can be increased and the following sub processes can be controlled more efficiently.

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